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Calculation of the Parameters of the Technological-Current Density Distribution during Wire Electrode Electrochemical Processing

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Abstract—This article is devoted to the calculation of the electrostatic field configuration in the interelectrode gap during electrochemical treatment using thin wire electrodes. The results calculated are experimentally verified. The possibility of predicting the accuracy of the detailed formation and for calculating the needed processing modes using the drawings of the applied perspective hybrid technology has been shown.

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INTRODUCTION

At the present stage of the development of material treatment technology, electrochemical methods are more widely used. Among the new and promising techniques for surfaces' processing (Fig. 1) is a wire electrode electrochemical one (WEECP) [1, 2].

The prospects of this technique are due to the fact that the production technologies that use a wire electroerosive process make high demands on the product parameters. This particularly concerns the surface roughness and the absence of a heat affected zone in the surface layers structure. It is difficult and expensive to meet these requirements in the framework of the material electroerosive destruction technology, and, in relation to the heat affected zone, it is practically impossible. The electrochemical method allows one in principle to efficiently treat surfaces with $Ra < 0.3$ μm in the absence of a heat affected zone. Despite the fact that the schemes and technological possibilities of dimensional electrochemical treatment are well enough investigated [3–6], the scheme of processing complex contoured linear surfaces using a thin wire electrode that moves equidistantly to the surface formed has remained poorly understood.

Thus, the development and improvement of WEECP as a treatment method is associated with the necessity for a comprehensive study of the basic physical and chemical processes occurring in the interelectrode gap (IEG). The set of technological processing parameters (the magnitude of the IEG (Δ), the composition, the temperature, the hydrodynamic features of the electrolyte flow, the amplitude–time parameters of the technological power source, and the electrode speed) defines the processes of the workpiece material's destruction and, accordingly, the surface parameters during WEECP. One of the most important and complex problems associated with WEECP is the distribution of the current densities in the IEG when using relatively thin wire electrodes (0.1–0.3 mm). The current density significantly affects the processes of the mass transfer at the metal–electrolyte interface and thus largely determines the quality of the resulting surface. This is an especially sharp problem in the case of profiled workpieces, where, unlike the traditional electrochemical processing, there needs to be achieves the process's localization and, hence, forming a controlled area of the technology's current spreading providing the required depth of removal and surface qual-

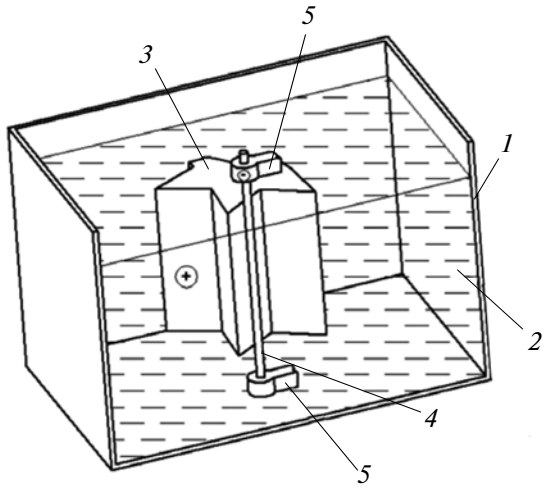

Fig. 1. WEECP scheme: (*1*) working electrolyte bath, (*2*) electrolyte, (*3*) workpiece under treatment, (*4*) wire electrode, and (*5*) wire electrode holders.

ity. In practice, this make it possible to control the process of the treatment and to predict its results.

STATEMENT OF THE PROBLEM

The anodic dissolution parameters in the treatment zone during WEECP (for the desired type and concentration of an electrolyte) can be varied by changing the distance between the electrodes and by selecting the wire electrode's diameter. Such changes allow obtaining different distributions of the interelectrode potential and thus obtaining different configurations of the electric field strength on the surface of the workpiece treated, which determines the current density and the degree of the process's localization. Thus, the aim of this work is to develop equations describing the distribution of the anode current density over the surface of a workpiece and equations allowing a formal mathematical description of the process of the anodic dissolution in the treatment zone during WEECP to be made.

THEORETICAL ANALYSIS

In general, the current density distribution between the electrodes is a function of the electrolyte's electroconductivity and the electric field's strength [7]:

$$j(x, y, z) = \kappa \cdot \vec{E}(x, y, z), \quad (1)$$

where κ is the electrical conductivity of the electrolyte, and x, y, and z are the coordinates of the accepted rectangular coordinate system.

The electric field's distribution in the interelectrode gap is characterized by the following expression:

$$\vec{E}(x, y, z) = -\text{grad}\varphi, \quad (2)$$

where $\text{grad}\varphi = \vec{k}\,\partial\varphi/\partial x + \vec{l}\,\partial\varphi/\partial y + \vec{m}\,\partial\varphi/\partial z$, and $\vec{k}$, $\vec{l}$, and $\vec{m}$ are the unit vectors along the x, y, and z axes.

When processing the flat surface of a workpiece by a cylindrical wire electrode, the problem of determining the potential distribution in the interelectrode gap is somewhat simplified.

Consider the case of WEECP in which the cathode is an infinite cylinder (wire) and the anode is a plane. The primary potential distribution $\varphi(x, y)$ in the IEG does not depend on the height and is a function of the distances from the cathode and anode surfaces, the cylindrical-cathode's radius, and the surface charge density. It can be calculated using the classical equations for the potential electrostatic field [7].

It should be noted that the best quality of the surface treated is observed at higher current values, and, hence, at a higher potential difference between the electrodes (the voltage of the external power supply). According to preliminary experiments carried out for the WEECP scheme, in the electrolyte used (a 6% solution of NaCl), the maximum potential difference is limited to a value 6 V, since large values of the voltage activate the formation of passivating films in the anodic dissolution area. As a consequence, the process's efficiency and the quality of the surface are degraded. The best surface quality when processing medium-carbon steel workpieces (30, 45, and 55 steel) using a brass wire electrode (L63) was obtained at a potential difference between the electrodes of 4 V, therefore, we will use precisely this voltage in our subsequent calculations.

The metal removal from the workpiece's surface depends not only on the initial potential distribution in the IEG but also on the total electrode potential (electrode polarization). According to [8], the total value of the anodic and cathodic potentials can be calculated as $\varphi(j) = 0.17 \ln(1 + j)$. This dependence was experimentally verified by the electropulse method [7] adapted to WEECP. The results of the experiments with sufficient accuracy coincide with those calculated by the proposed equation.

Experimental tests under the appropriate conditions for electrolysis in the WEECP have revealed features that allow making the following reasonable assumptions about the properties of the system:

—The capacity of the double layer insignificantly affects the polarization of the electrodes.

—At the studied regimes of electrolysis, there is no passivation of the electrode surfaces.

—At the required flow rate of the electrolyte in the IEG, there does not form any viscous pre-anode layer from the products of the reaction; therefore, the local concentration of the electrolyte does not change.

—There are no lateral flows of charges and masses on the anode's surface.

Thus, based on the assumptions made, in the WEECP, the anode current (Faraday) density is determined by the initial potential distribution in the interelectrode gap taking into account the anode and cathode polarization, which forms the parameters of the electrostatic field on the anode's surface.

The potential distribution in the interelectrode gap with consideration for the polarization of the electrodes is calculated using the software package MathCAD (Fig. 2).

As can be seen from the results of the calculations, with decreasing the distance between the cylinder and the plane, there increases the density of the equipotential lines in the IEG and therefore the degree of localization of the anode current should increase as well. Changing the wire electrode's diameter leads to a change in the field distribution around this electrode, but, directly in the electrode gap, changes in the field gradient have not been detected.

Material removal from the workpiece takes place according to the Faraday law by passing a current between the anode and the cathode surface of the workpiece. In this case, the nonuniformity of the anode current density results in uneven material removal from the workpiece. Figure 3 shows the calculated anode current density over the workpiece's surface.

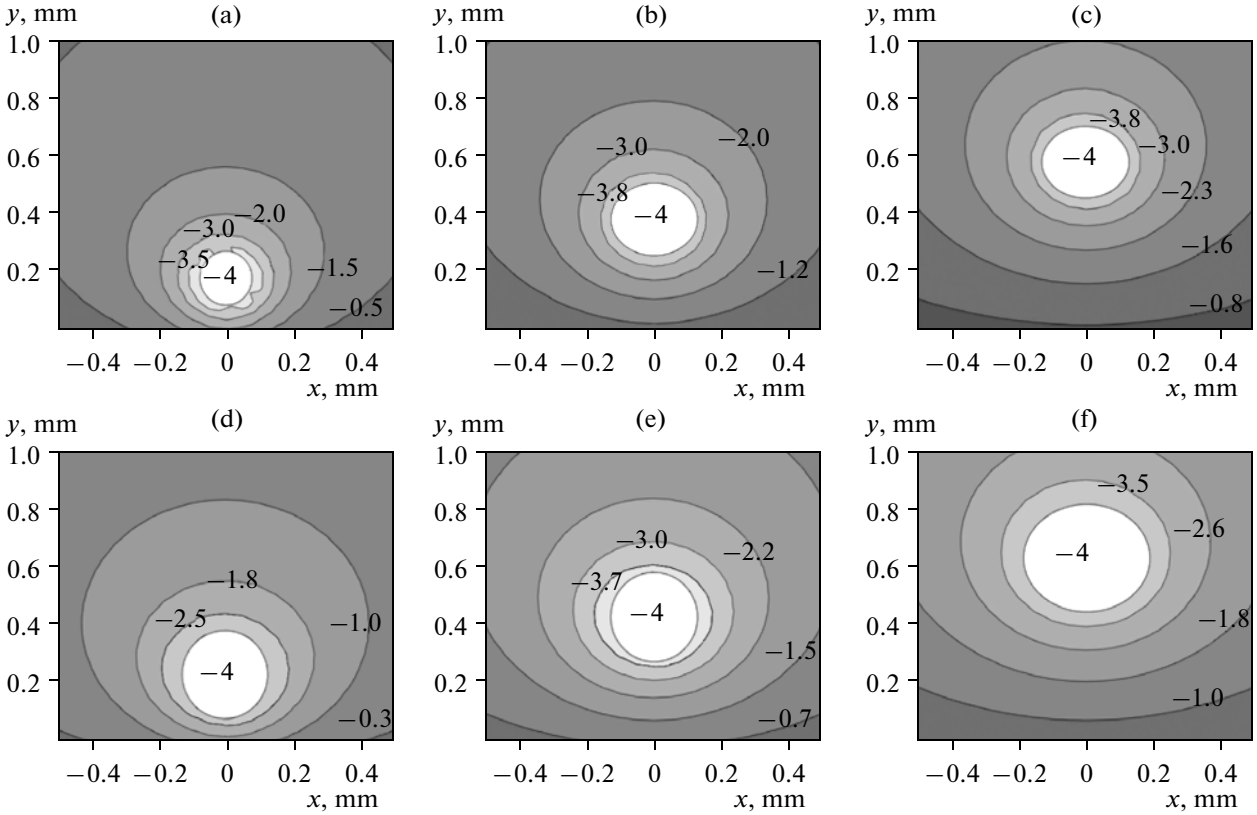

Fig. 2. Isopotential lines in the interelectrode gap between the cylindrical wire electrodes with diameters of (a)–(c) 0.15 mm and (d)–(f) 0.25 mm and the flat workpiece's surface for the following magnitudes of IEG: (a), (d) 0.1; (b), (e) 0.3; and (c), (f) 0.5 mm (at a potential difference between the electrodes of 4 V with considering the anodic and cathodic polarization).

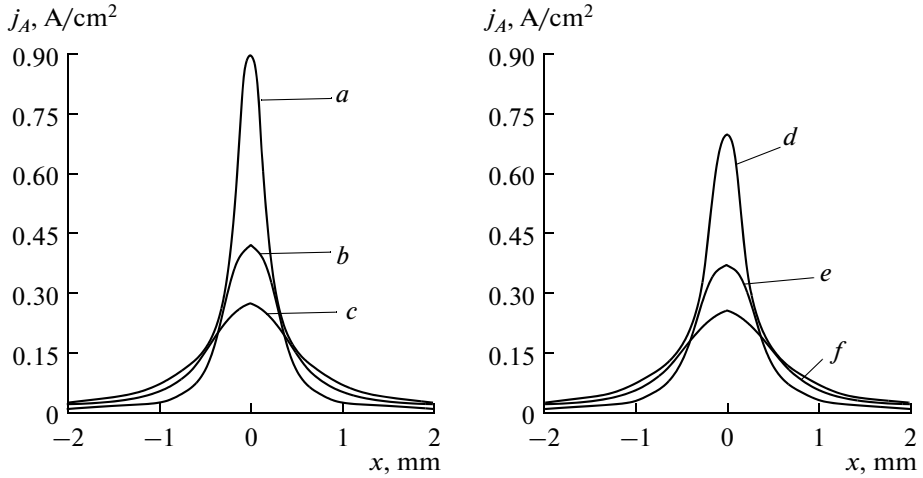

Fig. 3. Distribution of the anode current density over the anode surface in processing by electrodes with diameters of (*a*)–(*c*) 0.15 and (*d*)–(*f*) 0.25 mm for Δ = (*a*), (*d*) 0.1; (*b*); (*e*) 0.3; and (*c*), (*f*) 0.5 mm (6% aqueous NaCl solution with the specific conductivity $\kappa = 0.0871/(\Omega\ \text{cm})$).

For convenience, when predicting the results of the processing, the obtained curves (Fig. 3) should be described by mathematical functions.

Based on the above, let's find the anode current distribution over the workpiece's surface as a function of the interelectrode gap size for each of the electrodes used separately.

Taking into account the actual technological speeds of the equidistant wire-electrode movement to the treated surface (2–10 mm/min) and the results of

Parameters of normal distributions describing the calculated distribution of the anode current over the workpiece's surface

No.	Wire diameter, mm	IEG Δ, mm	*a*	σ	*b*
1	0.15	0.1	0.145	0.078	0.23
2	0.15	0.3	0.098	0.13	0.22
3	0.15	0.5	0.069	0.17	0.21
4	0.25	0.1	0.125	0.09	0.25
5	0.25	0.3	0.091	0.14	0.21
6	0.25	0.5	0.060	0.17	0.22

preliminary studies [8], it can be assume that a current density of less than 0.2 A/cm^2 practically does not affect the shaping in the processing zone. As can be seen from Fig. 3, the width of the zone in which the anode current density exceeds 0.2 A/cm^2 is less than 2 mm. Within this zone, the curves obtained can be described as a function of a normal distribution:

$$j_A(x) = \frac{a}{\sqrt{2\pi}\sigma} e^{-\frac{x^2}{2\sigma^2}} + b \ (\text{A/cm}^2). \qquad (3)$$

The parameters of the normal distributions obtained are listed in the table.

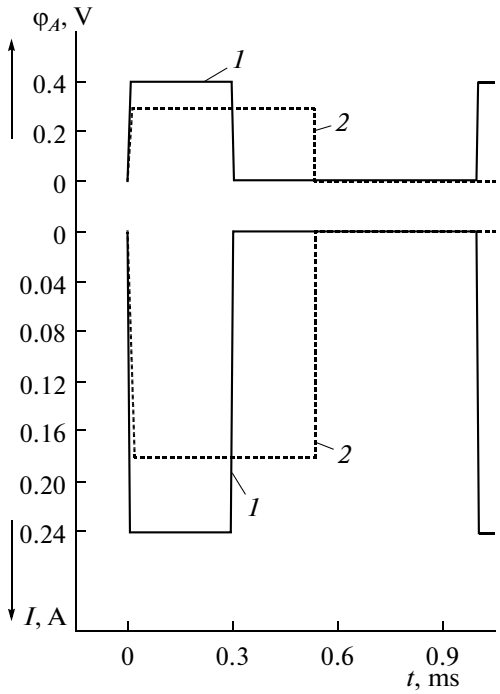

Fig. 4. Rectangular-shaped oscillograms of the anode polarization by the currents (the cathode is the wire DKRPM FKTL-63 electrode, ∅0.15 mm). The value of the interelectrode gap is as follows: (*1*) 0.3 and (*2*) 0.5 mm. The duration of the current impulses is as follows: (*1*) 300 and (*2*) 500 ms.

The dependence of the coefficients *a* and σ on the IEG's size is quadratic in nature. The coefficients *a* and *b* are directly proportional to the electrical conductivity κ of the electrolyte. The numerical dependences of the anodic current density over the workpiece's surface on the magnitude of the interelectrode gap were mathematically derived.

The equations obtained allow calculating, under certain constant values of the characteristics of the electrolyte, the anode current density distribution along the processed workpiece's surface for the case of wire electrode diameters of 0.15 and 0.25 mm, and the volume of material removed, respectively, in accordance with the Faraday law.

As a numerical parameter characterizing the degree of the WEECP process's localization, it is convenient to take the scale factor of the normal distribution function σ. As the table shows, the smaller the interelectrode distance Δ is, the smaller the value of σ, the less the zone of spreading of the current over the anode's surface, and the higher the process's localization are. A higher value of IEG corresponds to higher values of σ, the area of the anode current's spreading is wider, and the degree of the localization of the anodic dissolution process is smaller.

EXPERIMENTAL

For experimental verification of the assumptions and resulting calculations, a set of tests was performed. A rectangular workpiece 10 mm thick (45 steel, State Standard GOST 1050–88) was fixed and adjusted in the bath of a wire electroerosion machine. The tracking system of the machine (SELD-02M) and the technological conditions of the experiment provided ±0.01-mm accuracy of determining the relative position between the wire and the plane treated (the geometric value of the IEG). Studies were carried out for wire diameters of 0.15, 0.2, and 0.25 mm using the following geometrical values of the IEG: 0.5, 0.3, 0.2, 0.1, and 0.05 mm. The other basic process parameters were fixed (the voltage difference between the electrodes was $\Delta\varphi = 4$ V, the impulse frequency was $f =$ 1 kHz, the duration of the current impulses was $t =$ 300 μs, the composition of the electrolyte was a 6% aqueous solution of NaCl, the electrolyte's temperature was $T = 30$°C, the pressure in the washing nozzle was $P = 0.2$ MPa, and the process time for each position was $\tau = 300$ s).

Experiments have shown that, under the conditions of the electrochemical cell considered, in using the impulse mode of processing, the transients periods are less than 1% of the impulse's duration. Therefore, we can consider each isolated impulse as processing by the direct current, and the removal of material can be considered in accordance with the principle of superposition (Fig. 4).

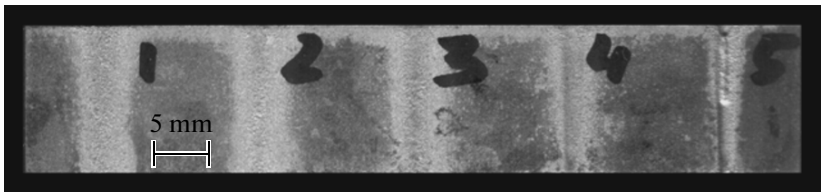

Fig. 5. Image of the processed plate obtained when using a wire with a diameter of 0.15 mm. Δ: (*1*) 0.5, (*2*) 0.3, (*3*) 0.2, (*4*) 0.1, and (*5*) 0.05 mm.

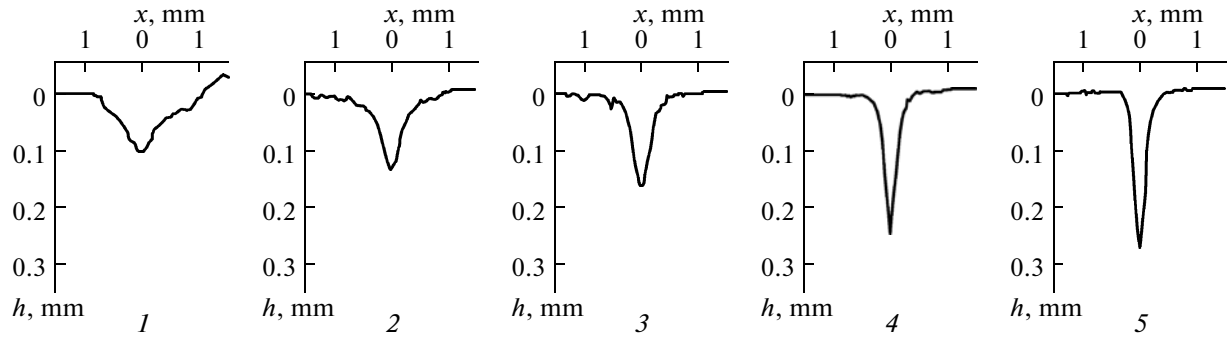

Fig. 6. Profilograms of the processed plate obtained when using a wire diameter of 0.15 mm. Δ: (*1*) 0.5, (*2*) 0.3, (*3*) 0.2, (*4*) 0.1, and (*5*) 0.05 mm.

The fixed electrode in the supplying voltage mode creates the electric field in the electrolyte during the impulse. The configuration of the field depends on the interelectrode gap and the wire's diameter. The potential distribution in the IEG determines the electric field strength's configuration over the anode's surface; the corresponding density of the Faraday current; and, consequently, the material removal speed in a specific workpiece place. There are formed grooves on the surface of the workpiece (Fig. 5), the profile of which correlates with the distribution of the currents in the electrode gap.

RESULTS AND DISCUSSION

The determination of surface profile was performed at the private research and production enterprise Microtech (Khar'kov, Ukraine) with a PM-210 profilometer. The resulting profilograms are shown in Fig. 6.

These profilograms leave no doubt that the surface profile located directly opposite the wire electrode significantly varies with the magnitude of the interelectrode gap. We used the experimental results to estimate the validity of the derived equations.

The metal mass removed from a unit of surface of the anode can be calculated by the following formula [7]:

$$m = \varepsilon_m \eta \int_0^\tau j_A(x) d\tau, \qquad (4)$$

where ε_m is the electrochemical weight equivalent of the metal, which is 0.0174 g/(A min) (for the ionization of bivalent iron); η is the current efficiency coefficient; and τ is the processing time.

The current efficiency coefficient is experimentally determined as the ratio between the theoretical material removal and the practically detected one.

Let us consider the plot obtained when processing with a wire with a diameter of 0.15 mm and an IEG value of $\Delta = 0.3$ mm. Based on the profilogram, we can calculate the area of the removed material and hence its volume and weight:

$$m_{\text{pract}} = S_{\text{prof}} h_{\text{workp}} \rho_{\text{st}} = 0.071\times10^{-2} \times 1 \times 7.8$$
$$= 5.6\times10^{-3} \text{ g}.$$

Substituting the value of the average current in equation (4) and taking the current efficiency coefficient equal to unity, we obtain the theoretically possible mass of the removed material:

$$m_{\text{theor}} = \varepsilon_m \eta I_{\text{av}} t = 0.0174 \times 1 \times 0.08 \times 5$$
$$= 6.96\times10^{-3} \text{ g}.$$

Consequently, the current efficiency coefficient under the experimental conditions is $\eta = 0.81$. A possible reason for a decrease in the current efficiency is the partial transition of iron into the solution in the form of trivalent iron.

The depth of the metal removal from the workpiece's surface at any point per impulse of *t*-second duration is given by the following:

$$m_x = \varepsilon_m j_A(x) t \eta, \text{ g/mm}, \qquad (5)$$

$$h_x = m_x \frac{k_{\text{imp}}}{\rho h_{\text{workp}}}, \text{ mm}, \qquad (6)$$

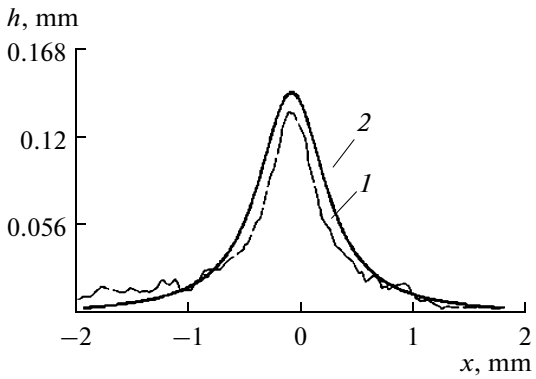

Fig. 7. (*1*) Experimental and (*2*) calculated profile of a groove (the wire's diameter is 0.15 mm, the IEG is 0.3 mm, and $\Delta\varphi = 4$ V).

where m_x is the specific weight of the material removed from the workpiece's surface at any point, $j_A(x)$ is the anode current density at the same point, h_x is the depth of the metal removal from the workpiece's surface at any point, k_{imp} is the number of current pulses during the whole process, h_{workp} is the height of the workpiece, and ρ is the density of the anode material.

As an example, Fig. 7 presents the results after the comparison of the groove profile as measured by a profilometer and calculated by the derived equations for a wire electrode diameter of 0.15 mm at an IEG value of 0.3 mm.

Similar calculations for all the experimental data have showed that the mass of the material removed differs from the calculated results by no more than 6%, and the removal depth, by no more than 7%, which can be considered quite satisfactory.

Based on the correlation of the experimentally obtained and theoretically calculated profilograms, it can be argued that it is possible to predict the surface profile during the electrochemical wire-electrode treatment. In this case, the numerical values of the calculated material removal depend on the parameters of the electrolyte (conductivity), the potential difference between the electrodes, the wire electrode's diameter, and the value of the interelectrode gap. Thus, it is possible to calculate the volume of material removed from the workpiece's surface and the corresponding change in the geometric dimensions using the known process parameters (including the speed of the wire electrode along the workpiece) or by solving the inverse problem, i.e., by calculating the appropriate parameters of the process using the necessary geometrical dimensions and the volume of the removed material.

CONCLUSIONS

(1) It was established that the degree of the process localization in the WEECP under certain constant values of the characteristics of the electrolyte was largely dependent on the distance between the wire cathode and the workpiece–anode. Changing the wire's diameter from 0.1 to 0.3 mm (the main range of wire diameters used in electroerosion machining) did not significantly affect the localization options.

(2) The parameters of the potential distributions in the interelectrode gap between the wire electrode–cathode and the anode–flat workpiece were calculated.

(3) The possibility of forecasting (at known values of the electrolyte characteristics, the wire-electrode diameter, and the interelectrode distance) of the actual material volume removed from the workpiece was shown.

(4) It is proved that the profile of the grooves formed by a fixed wire electrode correlated well with the derived equations for the anode current density distribution over the workpiece's surface.

(5) The elements of the system for calculating the parameters of a new promising method for electrochemical surface treatment by a wire electrode were created.

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