Microelectrochemical machining at the ultrasmall interelectrode gaps with the use of the packets of nanosecond voltage pulses

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Abstract

The accuracy of the electrochemical machining is determined by the value of the interelectrode gap (IEG). The stability of the process of the anodic dissolution at the ultrasmall interelectrode gaps is connected with the optimal dosage of the electric energy put into the electrolyser. The decrease of the IEG up to 10...20 μm demands of the narrow pulses of the voltage and small packets of pulses.

The work deals with the theoretical and experimental researches of the process of the electrochemical micromachining at the ultrasmall IEG with the use of the packets of pulses up to 100...200 ns.

The method of the envelope curves on the maximums of the current pulses in the packet of pulses is used to define the accuracy of the machining and the speed of the leveling of the initial accuracy of the machining.

The modeling of the process of the anodic dissolution at the ultrasmall IEG with the taking into account of gas generation and heating of the electrolyte.

The produced experimental plant was used to carry out the researches of the electrochemical micromachining with the use of the nanosecond pulses voltage.

Keywords: Electrochemical micromachining, packet of pulses, ultrasmall interelectrode gap

1. Introduction

Electrochemical micromachining (ECMM) is an effective method of production of microproducts from hardly processed materials having surfaces of a complex shape [1, 2]. It is connected with a number of indisputable advantages in comparison, as with traditional, and nonconventional methods of machining, the main of them are:

- an invariability of tool-electrode form throughout the whole processing;
- lack of the impacts on an tool-electrode leading to the change of its form or quality which allows to make low-rigid electrodes tools of minimum sizes.

Researchers in the field of the increase of accuracy of ECM are conducted in two main directions [3, 4]: reduction of an interelectrode gap up to the ultra small sizes (less than 1 micron) and reduction of duration of the power impact on a workpiece. And the latter is connected with the fast achievement of restrictions upon the transition to ultra small interelectrode gaps. The given condition led to that the electrochemical machining came out of the area of continuous introduction of energy to the working zone. At the moment the optimum technology decision from the point of view of the restriction of duration of the power influence, is the use of pulse and cyclic schemes at the electrochemical machining. Such a statement is confirmed by a large number of works on this subject, and also on the orientation of producers of the electrochemical equipment to use the pulse and cyclic schemes of ECMM. Despite it, there is an open question of technology parameters of processing on interelectrode gaps of an order of units of micrometers. Now the efficiency of the use of energy entering an interelectrode gap is insufficiently investigated.

The existing mathematical models [5 - 7] do not allow to determine rational ranges of parameters of the processing as the most number of theoretical researches consider single
pulses during the processing and have a large number of assumptions and restrictions. Also there are no techniques allowing to receive experimentally any empirical dependences describing the proceeding processes at electrochemical micromachining. All this allows to claim that the research of power and temporary parameters of ECMM on the ultra small interelectrode gaps using microsecond pulses of voltage is an actual task.

2. Problem definition

For determination of rational technological parameters of electrochemical micromachining on the ultra small gaps with the use of packages of microsecond pulses of voltage and, in particular, for the calculation of temporary characteristics of the entered energy in IEG it is necessary to define the indicator which in optimum characterizes the proceeding process. As such an indicator the coefficient of localization of \( K_L \) is in most cases used:

\[
K_L = \frac{\int_0^t \eta(t)I_1(t)dt}{\int_0^t \eta(t)I_2(t)dt},
\]

where \( \eta(t) \) is dependences of the anode current efficiency on time; \( I_1(t) \) is the functions describing the change of the current in the electrochemical cell in time.

At a constant current efficiency, the coefficient of localization (1) will be defined as a ratio of the sums of the areas of pulses of the current for two different interelectrode gaps (Fig. 1).

As the calculation of the area of a figure for each pulse in a package is quite a labor-consuming task, it was offered to use for the determination of coefficient of localization the theory of envelopes on maxima of separate pulses of current (Fig. 2).

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II. After the point \( T_n \) the conditions of the process in the ultrasmall IEG are significantly worsen, because of the intensive gas generation and bad conditions of the evacuation of the products of the electrode processes with almost motionless electrolyte. The considerable deterioration of the accuracy of the processing due to the inclusion into the processing of the side surfaces of the electrode tool is observed. In this regard the further analysis needs to be carried out by the search of an inflection point of \( T_n \) on the envelope on maxima of pulses of the current density. It is offered to determine rational parameters of the machining by taking into account the dosing of the energy entering into the interelectrode gap at the electrochemical micromachining on the ultra small IEG with the use of the packages of microsecond pulses of voltage.

It was assumed that such modes of the processing, at which the established value of the current density \( i_{nom} \) will be maximum, are the most preferable. It obviously testifies a continuous return to the initial conditions that respectively leads to the increase of the accuracy of the machining. For the theoretical definition of such modes, the limiting factors were separately analyzed, and the mathematical model which considers the heating and gas-filling of the electrolyte, and also the pulse and cyclic nature of the power process is developed.

3. Modeling of electrochemical micromachining

For the determination of the current density the one-dimensional model of the processes of the transfer in an interelectrode gap was used [8]. The flow of the gas-liquid mixture in IEG is described by average on IEG Navier-Stokes equations for a contracted viscous homogeneous two-phase medium:

\[
\frac{\partial W}{\partial t} + \frac{\partial F}{\partial x} = B,
\]

Fig. 1. Energy ratio for different IEG: (1) current pulses at \( s = 5 \) microns; (2) current pulses at \( s = 20 \) microns

Fig. 2. Definition of the transition zone of the current density in a package of pulses in the area of the established values: I - a processing zone with the maximum accuracy; II - a processing zone with the maximum productivity; \( i_{nom} \) is the established value of the current density in a package; \( T_n \) is an inflection point; \( T_{pac} \) is duration of a package of pulses of the current density.

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where

$$\mathbf{W} = \begin{bmatrix} \rho \\ \rho v \\ \rho v' \\ E \end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix} -\rho v^2 \\ \rho \sigma_v v \\ \rho \sigma_{v'} v' + S_p \\ Ev \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \eta \varepsilon_r j \\ (\eta_s \varepsilon_s + \eta_a \varepsilon_a) j \\ p \frac{\partial S}{\partial x} - \tau \\ U_j - Q_e - Q_w \end{bmatrix}.$$  

$x$ - coordinate along tool-electrode (TE) surface; $v$ - electrolyte velocity; $\rho = (1 - \varphi)S_p + \varphi \rho_g^{\varphi}$ - mass of a gas-liquid mixture in the IEG per unit area of tool-electrode surface; $\rho_x$ - density pure electrolyte; $\rho_g^{\varphi}$ - mass of gas in the IEG per unit area of TE surface; $\varphi = \varphi \rho / (\rho_p^{\varphi})$ - volumetric concentration of gas; $\rho^{\varphi} = p / (RT)$ - true gas density; $p$ - pressure; $R$ - gas constant; $T$ - temperature; $g = \rho \varepsilon / \rho$ - mass concentration of gas; $E = \rho c T$ - thermal energy of a gas-liquid mixture in the IEG per unit area of TE surface; $c_x$ - specific heat capacity of a pure electrolyte; $\eta_x$, $\varepsilon_r$, $\eta_a$, $\varepsilon_a$ - current efficiency and mass electrochemical equivalent for gas and workpiece material, accordingly; $j = \varepsilon_r (1 - \varphi)^{1/2} [1 + \beta (T - T_0)] U - \Delta U] / S$ - current density; $\sigma_{\varphi}$ - specific electroconductivity of pure electrolyte at the temperature $T_0$; $\beta$ - coefficient; $U$ - voltage; $\Delta U$ - voltage drop in the near-electrode layers; $\alpha_x = \frac{1}{|S|} \int \int S \mathbf{B} \cdot \mathbf{\xi} d\xi$ - Boussinesq coefficient, $\tau$ - components of tangential stress on the electrodes surfaces; $Q_e$ and $Q_w$ - heat fluxes to workpiece and TE, accordingly.

The state equation the mixture has a view:

$$\rho = \frac{S \rho_p p}{p + \rho_p RT g}.$$  

Good convergence of the obtained data when comparing with the data received at the calculations for the models offered earlier was revealed. The offered mathematical model provides a high accuracy by taking into account generation and heating of electrolyte.

As a result of the calculations it was established that the maximum the current density depends on the front of the pulse of voltage (Fig. 4) and increases at its reduction. So, for example, for 10% the water NaNO₃ solution and IEG equal to 5 $\mu$m, the maximum current density was about 1850 A/cm² with the duration of the leading edge, equal 50 nanoseconds. At the application of voltage pulses with duration of the leading edge, equal 200 microseconds, the maximum current density will make $\sim 250$ A/cm². Thus, the results received earlier about the importance of application of the voltage pulses with the nanosecond leading edge are confirmed.

Thus, the sharp decrease in the current density with the increase in the interelectrode gap is noted. So, for IEG equal 50 $\mu$m, the maximum current density was $\sim 350$ A/cm². Taking into account the use of the pulse and cyclic schemes, it was supposed that the pulse signal represents a rectangle with a certain duty ratio. Also when modeling of the
electrochemical micromachining on the ultra small interelectrode gaps it is necessary to consider an electrolyte relaxation during the pauses. The relaxation comes at the expense of a free exit from IEG of the products of the gas generation on the cathode on an edge gap. Thus, there is an updating of the electrolyte with return to initial conditions of the machining.

Fig. 4. The dependences of the current density on the duration of the pulse leading edge: 1 - \( T_f = 50 \) ns; 2 - \( T_f = 1 \) \( \mu \)s; 3 - \( T_f = 200 \) \( \mu \)s

The conducted researches showed that the established sizes of the density decrease with the increase in the duty ratio. So, for example, at the duty ratio of 30%, the established value of the current density makes about 350 A/cm² while at the duty ratio of 70% it is equal \( \approx 80 \) A/cm² (Fig. 5, 6). It proves the fact that efficiency of the process depends on the speed of recovery of the initial properties of the interelectrode environment. For the increase of accuracy packages with a small duty ratio are more effective.

Fig. 5. Dependence of the current density in the package of pulses from time at IEG \( s = 5 \) microns, duty ratio \( D = 30\% \)

It is possible to claim that with the increase in the interelectrode gap the influence of the duty ratio of pulses on the established current density decreases. So, the difference between the settled current density at duty ratio of 30% and 50% makes 80 A/cm². Thus, when using small IEG the possibility of short circuit increases.

Fig. 6. Dependence of the current density on time at IEG \( s = 5 \) \( \mu \)s, duty ratio \( D = 70\% \)

The carried-out analysis of the received results allowed to draw the following conclusions:
- with the reduction of the pulse-on time of the transition of the current to the area of the established values increases;
- with the reduction of the coefficient the increase in time of the transition of the current to the area of the established values is also observed;
- with the increase in the interelectrode gap, on the contrary, the reduction of time of the transition of the current to the area of the established values is observed.

As a result of the modeling of the process with the use of the dependences (2), the range of the rational parameters of processing is determined. Thus, not only the size of the established current density, but also the inflection point are considered, and the choice of the duration of the current pulses of and the block coefficient was defined concerning the size of the established current density. In turn, the duration of the package of the pulses was determined considering the inflection points of the envelopes by the maxima of the current pulses of for the chosen current pulses of and the block coefficient chosen duration. The obtained data are tabulated in Tab. 1.

| № | Modes Parameters | Parameters |
|---|------------------|------------|
| 1 | IEG, micron | 5 | 20 |
| 2 | Duration of a package, \( \mu \)s | 40 – 100 | 80 – 160 |
| 3 | Pulse duration, \( \mu \)s | 1 – 10 | 5 – 20 |
| 4 | Duty ratio, % | 20 – 40 | 30 – 55 |

Table 1

Rational modes of the electrochemical micromachining

It is necessary to notice that ranges of the modes depend on the required accuracy and productivity of the processing. So, for providing the most exact electrochemical micromachining the use of IEG less than 5 \( \mu \)m, the duration of the pulses of the current of 1-3 \( \mu \)s and the block coefficient of the voltage...
pulses, no more than 30% is reasonable. The duration of the packages of the current pulses of should not exceed 100 μs after which the washing of the interelectrode gap is necessary for updating of the electrolyte and return to the initial conditions of the processing. The electrolyte needs to be chosen with the maximum localizing ability and conductivity no more than 7 S/m.

4. Experimental studies of the electrochemical micromachining

Experimental studies were carried out on the equipment providing the pulse and cyclic mode of the ECMM. For the registration and record of the form of the packages of the current pulses the oscillograph digital memorable WaveAce1012WA series, connected to ACS756CA-050B current sensor was used. The received images of oscillograms of forms of the packages of the current pulses remained on USB flash carrier in the BMP format, then they were transferred to the personal computer and brought in the database for after treatment. For digitization of the received oscillograms the ChartReader program was used.

For the record of the current density the special current shunt was used. It should be noted that key feature of the used current shunt consists in impossibility of receiving results of measurement of the current density in the first 1 - 5 microseconds of the pulse owing to what it is impossible to record peak values in the ultra small gaps.

As a result of the conducted researches the oscillograms of the forms of the current pulses for the different modes of the electrochemical micromachining were received.

So, for example, the greatest maximum current density was received at the interelectrode gap of 5 μm and was 400 A/cm², while for the gap of 50 μm the maximum current density was 170 A/cm², that is coordinated with the data obtained in works [9, 10] and also at the mathematical modeling of the process of the electrochemical micromachining.

After the digitization and the analysis of oscillograms of the packages of the current pulses groups of the envelopes for different conditions and the modes of the processing were received. The envelopes for different interelectrode gaps are presented on Fig. 7.

According to the obtained data, it is possible to draw a conclusion on inexpediency of the use of the large pulse duration and the high duration ratio of the voltage pulses and the big packages of the voltage pulses. Such a combination leads to a sharp decrease in the coefficient of localization, which negatively affects the processing accuracy.

The use of the minimum durations of the voltage pulses, the packages of the voltage pulses, duration ratio of the voltage pulses leads to a significant increase in the coefficient of localization and according to the processing accuracy. But thus the productivity of the electrochemical micromachining essentially decreases. Proceeding from the obtained data the rational modes of the electrochemical micromachining with the use of the packages of microsecond pulses were offered.

With the use of the offered technology modes the processing of workpiece for the purpose of receiving shaped surfaces with the subsequent measurement of precision characteristics was carried out. The researches allowed to specify the obtained data, which is necessary for the development of recommendations on carrying out the electrochemical micromachining with the use of the packages of microsecond pulses of the voltage.

For an assessment of the extent of the copying of the initial roughness, the electrode tool with an artificial macrorelief in the form of the ring grooves received after turning, the depth ~ 26 μm was made. Tool-electrode is made of LO 70-1 brass (State standard specification 15527-70) and have openings for pumping of the electrolyte in the course of washing of the interelectrode gap. The measurement of macrogeometry of the received shaped surfaces on workpiece was performed on the Kosaka Lab profilografe-profilometer Surfcorder SE 17000-39.

The cavities of 300 μm in depth were received. The processing was carried out with an amplitude of pulses of 12 V of 10% water aquosystem of NaNO₃. The accuracy of the copying of macrogeometry was evaluated on the value of the roughness of Rz = 26 μm on the electrode tool. The accuracy of machining is determined as maximum deviation of the cavity surface from the offset surface, which drawn from TE by the value of IEG. The roughness of the cavity surface is copied from roughness of TE due to a very small IEG. The processed cavities are given in Fig. 8.

Fig. 8. Results of the processing on IEG of the different sizes under other identical conditions: (a) IEG of 50 μm; (b) IEG of 15 μm; (c) IEG of 5 μm

The experimental studies allowed to draw a conclusion that the average density of current increases with the reduction of the interelectrode gap. In particular, for IEG s = 50 μm the average density of the current was 87 A/cm², while for s = 5 μm - 137 A/cm² that is by 1.57 times more. Thus, it is necessary to note that the reduction of IEG to 1 μm on these
It is also possible to note that with the reduction of IEG processing speed with 8.7 increases to 21.5 microns/min., i.e. by 2.47 times. It is connected with increase in the average current density and its peak values, which reached 1200 A/cm².

The almost insoluble area on the workpiece surface formed as a result of a short circuit when processing on IEG equal 1 μm did not allow to carry out the processing on depth of 300 μm. Thereof the data on speed, surface roughness and time of the processing for the interelectrode gap equal to 1 μm were not obtained.

5. Conclusions

Modeling of the process of the electrochemical processing is executed by the packages of microsecond pulses when using ultra small IEG. The envelopes on maxima of pulses are obtained on the basis of the analysis of the coefficients of localization of the process of the anode dissolution the effective duration of the packages of the voltage pulses are received.

The received rational technology modes of the electrochemical micromachining on the ultra small interelectrode gaps using microsecond pulses of the voltage became the results of the conducted pilot studies of the forms of the packages of the current pulses the proceeding in the electrochemical cell and envelopes of the current pulses. It is proved that for achievement of the error which is not exceeding 10 microns it is necessary to use interelectrode gaps less than 10 μs Tp in the range of 1 - 10 μs, Tpac in the range of 50 - 100 ms, D in the range of 20 - 30%.

The received results confirm the possibility of the use of the electrochemical micromachining for receiving microcavities and microproducts. Further, it is necessary to conduct researches in the field of the ultra small interelectrode gaps regarding identification of a new area of the processing without short circuits.

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