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Approach to setting the mode parameters in combined electro-erosive - electrochemical processing during piercing the deep holes of small diameter

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Approach to setting the mode parameters in combined electro-erosive - electrochemical processing during piercing the deep holes of small diameter

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Abstract. The article considers the problem of forming the deep holes of small diameter by using the combined electro-erosive and electrochemical machining based on the electrochemical and electro-erosive processes. The approach to setting the mode parameters during piercing the deep holes with a diameter of less than 1 mm is suggested. The approach takes into consideration the influence of hydrodynamic losses in the inter-electrode gap on the limitation of the mode parameters of the electrochemical and electro-erosive components in the combined processing. It also takes into account the interrelation between the magnitude of the inter-electrode gap and the linear velocities of the removal of the processed material in each of the components during the combined processing. The validity of the approach to setting the mode parameters in the combined electro-erosive - electrochemical processing during piercing the deep holes with a diameter from 0.3 mm to 1 mm in the range of the inter-electrode gap from 0.025 mm to 1 mm is experimentally confirmed.

1. Introduction

Much attention in modern production for piercing the deep holes of small diameter in the range from 0.3 mm to 1 mm in parts of different application is paid to the methods, based on electro-physical and electrochemical processes of removing the machined material [1 – 10]. It can be explained by the fact that piercing of such holes by traditional methods of mechanical processing is connected with considerable difficulties due to low strength and insufficient rigidity of the cutting tool, the problems of the chip removal from the hole and the difficult feed of the lubricating-cooling liquid in the cutting zone. To solve the technological matters concerning piercing the deep holes with a diameter of less than 1 mm, the electro-erosive and electrochemical methods of forming based on copying the tool shape in the machined material are considered to be perspective. However, each of these methods is based on implementing different physical processes to remove the material and has its own range of technological possibilities.

In recent years the combined methods based on using different physical and chemical processes are effectively developed. For instance, the combined process of electro-erosive - electrochemical machining is used for forming different surfaces. The possibility of combining совмещен these processes in one processing is explained by a favorable machining of the conditions for their implementation in the inter-electrode gap. This fact was mentioned by Lazarenko B.R., the founder of the electro-erosive processing in the mid-twentieth century [11].

It is pointed out [7] that combining the electrochemical and electro-erosive processing is effective for solving the technological matters concerning the piercing of the small diameter holes in parts. It provides the increase in productivity by 5-10 times in comparison with the traditionally used electrochemical dimension processing [6]. Besides, there is information [2] that to implement the combined electro-erosive and electrochemical processing, a number of electrochemical printing-broaching machine are upgraded for producing the elements of the combustion chamber, piercing the lubrication holes in the bearing rings, perforating the thin-walled rings and some other parts at the aircraft enterprises.

Thus, considerable results concerning the implementation of the combined electro-erosive - electrochemical processing of holes are achieved in practice [7]. However, in spite of the results obtained, the question on setting the mode parameters in the combined electro-erosive - electrochemical processing during the piercing of holes in the range from 0.3 mm to 1 mm remains open.

2. Statement of the problem

It is pointed out in papers [6, 7] that the possibility of combining the electrochemical and electro-erosive processes in one machining is explained by the fact that both methods of piercing the holes are implemented according to same technological scheme by using the hollow cathode-tool during a continuous feed of the technological liquid in the inter-electrode gap through its central hole. The scheme of a moving hollow cathode-tool with the uniform electro-isolation coating is presented in papers [12, 13]. It was used in the investigation mentioned for piercing the deep holes of small diameter in the range from 0.3 mm to 1 mm. The scheme of the hydraulic path, formed during the combined electro-erosive -electrochemical piercing by a hollow cathode-tool with the electrically insulated coating is presented in Figure 1.

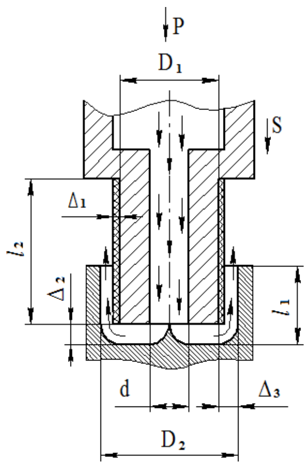

Figure 1. Scheme of the hydraulic path, formed during the combined electro-erosive - electrochemical piercing by a hollow cathode-tool with the electrically insulated coating [12, 13]

The scheme shows the geometry and the parameters, which form the hydraulic path:

D_1 – cathode-tool diameter;

D_2 – hole diameter;

d – hole diameter in the cathode-tool;

l_1 – hole length;

l_2 – cathode-tool length;

Δ_1- thickness of the isolation coating;

Δ_2 – inter-electrode gap;

Δ_3 – side inter-electrode gap;

S – supply of the cathode-tool;

P – excessive pressure of the technological liquid.

It should also be mentioned that the combined processing is done at values of the inter-electrode gap used for the electrochemical processing, which excludes the possibility of stopping the flow of the technological liquid and appearing short circuits of the electrodes.

According to the results of the research made by Lazarenko B.R. [11], the electrochemical component in the combined processing is considered to be the main. It means that high voltage pulses of the electro-erosive machining in this processing are overlapped on the self-running process of the anodic dissolution. This statement is based on the fact that the electrolyte is used as a technological medium in the combined machining, which is typical of electrochemical processes, while the electro-erosive processing is used in the dielectric liquid.

The author of Paper [11] explains that the kinetics of developing the electrode processes in the electrochemical dimension machining is connected with the fact that the inter-electrode gap during the electrolysis is filled with gaseous reaction products, which increases its ohmic resistance. The formation of the gas-vapor layer in the inter-electrode gap prevents the anodic dissolution of the material processed. The electric breakdown of the gas-vapor layer for providing the conductance channel requires the use of pulse voltage. Thus, if we apply the high pulse voltage, beside low constant voltage, to the electrodes of the electrochemical unit, which is sufficient for the breakdown of the gas-vapor layer in the inter-electrode gap, two processes – the anodic dissolution with forming the gas-vapor layer and its electric breakdown with forming the conductance channel appear in this case.

In accordance with the recommendations on choosing the mode parameters in using the electrochemical dimension processing [14, 15] in piercing the holes with a diameter of 2 mm and higher, it is necessary:

- to choose the electrolyte with a maximum value of the current efficiency of the processed metal and with maximum electric conductivity, which is provided at a limit concentration of the solution;
- to apply the maximum possible values of the technological voltage which the exclude the appearance of electrode short circuit.

The recommendations cannot be applied directly to piecing the holes with a diameter of less than 1 mm. It is explained by the fact that in processing such holes the hydrodynamic limitations caused by the necessity of implementing the electrochemical dimension processing at small values of the inter-electrode gap are intensified. In decreasing the inter-electrode gap, the velocity of the anodic dissolution increases and the intensity of removing the processing products reduces because of the drop in the excessive pressure of the technological liquid in narrow parts of the hydraulic path. Its scheme is shown in Figure 1. As a result, there is a destabilization of the conditions of the electrochemical dimension processing.

It is known [14] that the value of the excessive pressure of the technological liquid during the electrochemical dimension processing is an order lower than in the electro-erosive processing (7 – 10 MPa) and does not exceed 0.8 – 1.0 MPa. The use of pressures, typical of the electro-erosive processing, in the electrochemical dimension machining inevitably leads to the appearance of the cavitation processes in the inter-electrode gap of the hydraulic path. It results in the separation of the electrolyte flow and the formation of so-called “dry zones”, which is unacceptable in the electrochemical dimension processing. Paper [14] shows that to implement effectively the electrochemical dimension processing, it is necessary to use the flow of the technological liquid with the Reynolds number in the range of 2 500 …. 4 000.

In addition to it, the presence of the isolation coating of a finite thickness on the side surface of the cathode-tool, which excludes the etching of the hole, a considerable length of the hydraulic path and low rigidity of the cathode-tool greatly influence the appearance of the hydrodynamic processes in the parts of the hydraulic path which scheme is presented in Figure 1. As a result, there is a decrease in the flow velocity of the technological liquid during the hole piercing.

The present paper is devoted to reasoning the approach for imposing the mode parameters in the combined electro-erosive - electrochemical processing in piercing the deep holes of small diameter with account of hydrodynamic processes in the inter-electrode gap.

3. Theoretical and practical significance

The well-known thesis of the theory of the electrochemical dimension processing shows the interrelation of the linear velocity of the anodic dissolution of the metal machined and the mode parameters of the process [14]:

$$V_1(S) = \frac{k \times \chi \times U \times \eta}{60 \times \Delta_2 \times \gamma}, \text{ [sm/min]} \tag{1}$$

where

k – electrochemical equivalent of the machined metal, g/A$\times$h;

χ – electric conductivity of the electrolyte, om$^{-1}\times$ sm^{-1};

U – technological voltage, V;

η – current efficiency of the processed metal;

Δ_2 – inter-electrode gap, sm;

γ – specific weight of the metal machined, *g*/sm^3.

The equation (1) shows the self-adjusting character of the anodic dissolution of the machined metal during the relative motion of the electrodes. It means that there is such current density in the direction of motion of one of the electrodes, at which the velocity of the electrochemical dissolution (V_1) is equal to the supply (S) of the electrode motion.

To assess numerically the parameters of the electrochemical process, it is necessary to determine the rational ranges of varying mode parameters during machining. It follows from Equation (1) that the maximum velocity of the anodic dissolution of the materials is achieved at the maximum localization of the process (at minimum possible value Δ_2), the maximum permitted value of the technological voltage and the using an electrolyte limit concentration of the solution. The statement is valid for processing any conductive material.

Taking into consideration the above said, theoretical results are obtained in Paper [13], which show the position of the curves of the linear velocity of the anodic dissolution (feed) in the electrolyte (the technological liquid) during material processing in the specified range of values of the inter-electrode gap.

Figure 2 presents graphically the scheme of the equation (1) during the electrochemical dissolution of copper M1in the specified ranges of values of the technological voltage and the inter-electrode gap [13]. The area of the mode parameters shown in the scheme is limited by the minimum value (U_{min} = 5 V) and maximum value (U_{max} = 20 V) of the technological voltage, the inter-electrode gap (from 0.025 mm to 0.1 mm) and the line of the maximum allowed supply (S_{max} (Re = 2 500)).

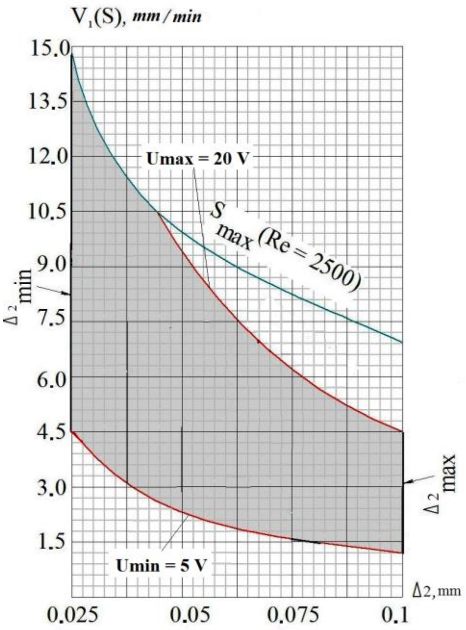

Figure 2. Ratio of the linear velocity of the anodic dissolution (supply of the cathode-tool) of copper M1 in 30% $NaNO_3$ and the inter-electrode gap [15]

The limitation of the technological voltage by a value of 20 V excludes the appearance of electro-erosive discharges in the inter-electrode gap, thus providing the integrity of the cathode-tool and not worsening the quality of the processed surfaces [14]. The minimum value of the technological voltage, equal to 5 V, is determined by the efficiency of developing the processes of the electrochemical dissolution [14]. The adjustment of the minimum value of the inter-electrode gap at a level Δ_2 = 0.025 mm is connected with excluding the appearance of obliteration, which prevents the electrolyte motion in the processing zone [14]. The limitation of the maximum value Δ_2 = 0.1 mm is determined by the tendency of the maximum approximation of the diameter of the formed hole to the diameter of the cathode-tool. The position of the upper boundary of the mode parameter zone is determined by the technological voltage, electric conductivity of the technological liquid used and the maximum allowed velocity of the anodic dissolution (supply S_{max}). The supply of the cathode-tool for providing the constant inter-electrode gap in the electrochemical dimension processing must be equal to the velocity of the anodic dissolution. On the one hand, the line of the maximum allowed velocity of the anodic dissolution provides the flow velocity, which does not lead to the appearance of the cavitation of the technological liquid in the inter-electrode gap. But, on the other hand, it provides the whole removal of anodic dissolution products by the flow of the technological liquid from the inter-electrode gap. It is described by the empirical equation [14]:

$$V \geq 4 + 0{,}6S^2 \quad (2)$$

where

S – electrode supply, mm/min;

V – flow velocity of the technological liquid in the inter-electrode gap, m/s.

Although there is certain information on the results (Figure 2), which describe the interrelation between the linear velocity of the anodic dissolution at the relative motion of the electrodes and a value of the inter-electrode gap, the equation (1) does not consider the hydrodynamics of the technological liquid flow during its motion along the whole inter-electrode gap (the hydraulic path). Geometry of the hydraulic path depends on the scheme of the electrochemical piercing of the hole.

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To provide the optimum flow velocity of the technological liquid in the operating zone of the inter-electrode gap (Δ_2 Figure 1), it is necessary to create the excessive pressure (P) at the entrance to the hydraulic path. Its value determines the hydrodynamic mode in the inter-electrode gap, which depends on hydraulic losses in local resistances in the inter-electrode gap of the hydraulic path. The losses are caused by changing the flow cross sections, turnings and the friction of the technological liquid along the cathode-tool motion.

The value of local losses is determined by Weisbach equation [16]:

$$\Delta P_i = \xi_i \cdot \frac{\rho \cdot V_i^2}{2}, \tag{3}$$

where ΔP_i - local losses;

ξ_i - coefficient of local hydraulic resistance;

ρ - electrolyte density;

V_i - velocity of the electrolyte flow.

According to Equation (3), the total hydraulic losses in local resistances of the hydraulic path must be equal to the value of the excessive pressure of the technological liquid at its entrance. In its turn, the flow velocity in the operating zone of the inter-electrode gap for the required piercing depth must not be lower than the value determined by Equation (2). The decrease in the flow velocity of the technological liquid in the operating zone of the inter-electrode gap to the value determined by Equation (2) proves obtaining the limited depth of hole piercing.

The detailed calculation of hydraulic losses in local resistances of the hydraulic path is presented in Paper [13] for the scheme in Figure 1 by using Equation (3).Theoretical results as lines of maximum attainable depths in piercing the holes with a diameter of less than 1 mm by the cathode-tool with the ratio of the inner and outer diameters of 0.7 mm to 0.9 mm at the thickness of the isolation coating Δ_1 = 0.02 mm and Δ_1 = 0.05 mm located in the zone of mode parameters are presented in Figure 3.

It should be noted that the necessity of providing the accuracy of forming according to the length of the pierced hole causes the use of the cathode-tool with the isolated side surface. The presence of the isolation coating on the tool decreases the cross section in the side inter-electrode gap, thus increasing the losses of the hydraulic pressure and limiting the depth of the hole piercing.

Paper [13] shows that the increase in the thickness of the isolation coating of more than 0.02 mm reduces the zone of the mode parameters. In this case, the boundary determined by the value $\Delta_{2\,min}$ displaces to higher values of the inter-electrode gap (Figure 3).

In addition to the problems connected with the appearance of hydrodynamic pressure losses, there are limitations caused by low rigidity of the tubular cathode-tool during piercing the deep holes of a small diameter. Because of hydrodynamics of the electrolyte flow, there are self-oscillations of the cantilevered cathode-tool, which can lead to the short circuit of the electrodes and the damage of the tool and the processed surface. The attempt of increasing the rigidity of the hollow cathode-tool by changing the inertia moment of its cross section (which is possible only in decreasing the hole diameter) results in a considerable displacement of the boundaries of the mode parameters zone and a significant decrease in the range of attainable depths of piercing [13].

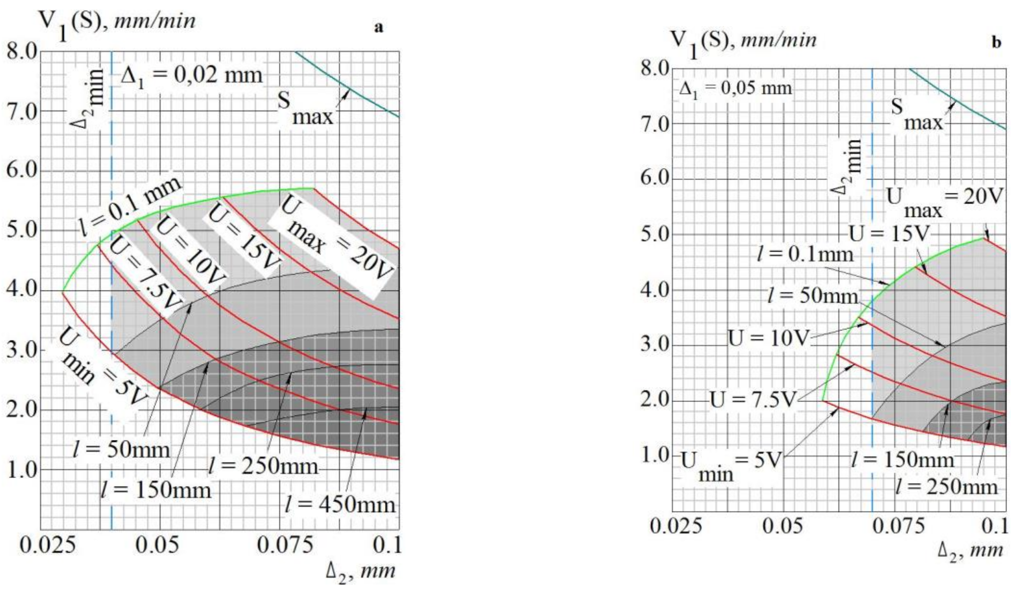

Figure 3. Lines of maximum achievable depths in the zone of the mode parameters of the electrochemical piercing of the hole in copper M1 by the cathode-tool with the ratio of diameters from 0.7 mm to 0.9 mm in 30% $NaNO_3$ at pressure P = 1.0 MPa and thickness of the isolation coating: a - Δ_1 = 0.02 mm; b - Δ_1 = 0.05 mm [13]

Thus, to provide a constant process of the electrochemical dimension machining the following approach to setting the mode parameters in piercing the holes of the dimension range of 0.3 to 1 mm is suggested:

- to choose the cathode-tool maximum approximated to the diameter of the pierced hole;
- to determine the calculated value of the inter-electrode gap which can provide the achievement of the required depth of the hole piercing;
- to determine in advance the value of the cathode-tool supply;
- in accordance with Equation (1) to calculate the required value of the technological voltage according to the specified values of the cathode-tool supply and the inter-electrode gap;
- to clarify the corresponding value of the cathode-tool supply according to the specified value of the calculatedinter-electrode gap (Δt).

The approach mentioned allows us to determine the mode parameters of the electrochemical forming in the absence of the surface passivation. However, in using practically the electrochemical dimension processing of conductive materials there appear in most cases passivation phenomena, which considerably decrease and for some metals fully block the process of the anodic dissolution. The passivation of the processed surface can be revealed in decreasing the electrochemical equivalent (k) of the metal, which is confirmed by the results of potentiostatic investigations of the anode behavior of metals and alloys [13].

In practice there are different mechanisms of the activation of the electrochemical dimension machining, and the schemes of the combined processing such as electro- diamond grinding, laser-electrochemical processing, electro-erosive – electrochemical processing are developed. To form the deep holes of a small diameter, the electro-erosive – electrochemical processing is considered to be the only method when constant updating of the anode surface is provided by discharge pulses.

The introduction of high-voltage pulses in the inter-electrode gap during the electrochemical forming of the energy level provides repeated updating of the anode surface for a second, excluding its passivation by oxide films [13]. In this case, the electro-erosive influence causes its own mechanism of removing the processed material, providing the achievement of a certain linear velocity of the electro-erosive destruction (V_2).

To provide the efficiency of the combined processing, it is necessary to remove not only the products of the electrochemical dissolution but also of the electro-erosive destruction from the inter-electrode gap fully and in time. So, in setting the mode parameters of the combined electro-erosive – electrochemical machining calculated according to the hydrodynamic limitations, the value of the linear velocity of the material removal presents the sum of the linear velocities as a result of two mechanisms of its removal (Figure4). Then, the equation (2) applied to the combined processing can be presented as follows:

$$v \geq 4 + 0{,}6\,(V_1 + V_2)^2. \quad (4)$$

Paper [17] shows that the linear velocity of the electro-erosive destruction (V_2) can be presented by the empirical equation as a function of the mode parameters of high-voltage pulses, thermo-physical characteristics of the processed material and the hole diameter in the following way:

$$V_2 = \frac{240 \cdot K \cdot W \cdot \mathrm{f}}{\pi \cdot D^2}, \text{ (mm/min)} \quad (5)$$

where

$K = k_1 \cdot k_2 \cdot k_3^2 \cdot 10^{-9}$ - specific erosion, [mm^3/μJ], proportional to the coefficients of a shape (k_1), depth (k_2) and squared coefficient of the hole diameter (k_3) formed by one discharge;

$W = K\dfrac{C_2 \cdot U^2}{2}$ - pulse energy, [μJ], spent on the destruction of the processed material by taking into account the losses (K) in the discharge channel;

C_2 – storage discharge capacitor;
U – pulse voltage;
f – frequency of the pulse repetition, [Hz];
D – diameter of the formed hole, [mm].

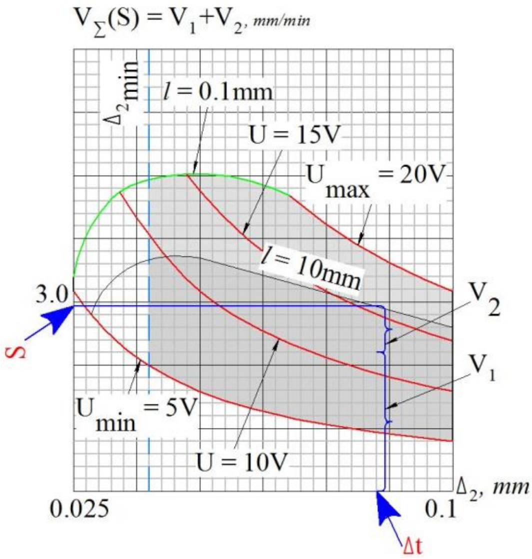

Figure 4. Ratio of the total linear velocity of the electrochemical and electro-erosive components and the inter-electrode gap during the combined piercing of holes [13]

A part of the linear velocity of the combined processing established according to Equation (4) and belonging to the electrochemical component allows us to calculate the values of the mode parameters of the process mentioned in accordance with Equation (1). It must be noted that in piercing the holes in a certain material by using the chemical composition of the technological liquid of specific concentration, the technological voltage remains a varied mode parameter of the electrochemical process. It is possible to control the linear velocity of the electrochemical component by varying the electric conductivity of the electrolyte due to changing its concentration or the chemical composition. For instance, the use of electrolytes with a lower concentration leads to decreasing the linear velocity of the electrochemical dissolution of the material processed and increasing the integrity of the technological equipment and safety of the personnel. The required linear velocity of the electro-erosive destruction of the material processed is determined according to the total depassivation of the anode surface.

The theoretical results presented above in the investigation allow us to develop the following approach to setting the mode parameters for the combined electro-erosive –electrochemical piercing of holes with a small diameter:

- to calculate the zone of the mode parameters of the electrochemical dissolution of the processed material in the corresponding electrolyte according to Equation (1). It must be limited by maximum and minimum values of the technological stress and the value range of the inter-electrode gap intended for piercing the holes of small diameter. It must also be limited by the line of maximum allowable supplies which exclude the cavitation;
- to calculate the position of the lines of maximum allowable depths of piercing in the zone of mode parameters;
- to calculate the value of the inter-electrode gap according to the prescribed diameter of the hole and the diameter of the cathode-tool, which is maximum approached to the diameter of the pierced hole;
- to set maximum and minimum modes of the linear velocities of the electrochemical dissolution according to the calculated value of the inter-electrode gap and the required depth of the pierced hole;
- to calculate the technological stresses corresponding to the maximum modes of the electrochemical dissolution;
- to choose from the calculated values of the mode parameters the variants which implement the electrochemical machining in the combined processing;
- to calculate the required linear velocity of the electro-erosive removal of the material for the chosen parameters of the electrochemical dissolution and the value of the maximum velocity of the processing which allows us to obtain the required depth of piercing;
- to calculate the mode parameters of the electro-erosive process using Equation (5) – voltage, capacity of the storage discharge condenser (the pulse duration), the frequency of pulse repetition;
- to determine the supply of the cathode-tool in the combined processing as a sum of the linear velocity of the electrochemical and electro-erosive components;
- to provide the observance of the following condition – a combination of the inter-electrode gap and the total linear velocity of the electrochemical and electro-erosive components in the combined processing must be lower than the line of the maximum achievable depth (Figure 4).

Non-observance of the condition mentioned will lead to breaking the stability of the forming process of the hole. The experimental results of the investigation are presented in Paper [13].

4. Conclusion

The approach to setting the mode parameters for piercing the deep holes of small diameter in the range of the inter-electrode gap from 0.025 mm to 1 mm is suggested on the basis of the theoretical analysis and experiments of the combined electro-erosive – electrochemical processing. The approach is done by taking into consideration the hydrodynamic losses in the inter-electrode gap, revealing the interrelation between the linear velocities of the removal of the processed material and the value of the inter-electrode gap in the range of its values, providing the hole forming of the dimension range mentioned. The boundaries of the zone of the mode parameters in the combined processing are determined as lines of the maximum achievable depths of hole piercing in the zone of mode parameters of the electrochemical component. It is carried out by using the calculations of the hydrodynamic mode. The validity of the approach to setting the mode parameters in the combined electro-erosive – electrochemical machining during piercing the deep holes of a diameter from 0.3 mm to 1 mm in the range of the inter-electrode gap from 0.025 mm to 1 mm is confirmed by taking in account the hydrodynamic processes in the inter-electrode gap. The possibility of redistributing the linear removal of the processed material between the electrochemical dimension processing and the electro-erosive processing within the combined impact is presented.

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