ISSN 1068-3755, Surface Engineering and Applied Electrochemistry, 2019, Vol. 55, No. 6, pp. 621–629. © Allerton Press, Inc., 2019.
Russian Text © The Author(s), 2019, published in Elektronnaya Obrabotka Materialov, 2019, No. 6, pp. 1–10.

Determination of Power Factors Affecting Surface Formation in the Process of Electrical Discharge Machining

V. I. Osypenko[a], and O. P. Plakhotnyi[a, *]

[a]*Cherkasy State Technological University, Cherkasy, 18006 Ukraine*

**e-mail: o.plakhotny@chdtu.edu.ua*

Received June 20, 2018; revised July 23, 2018; accepted July 23, 2018

Abstract—The results of experimental and theoretical studies of the creation of experimental and calculation methods are presented for the determination of the value of a distributed external load, which affects a wire during electrical discharge machining of certain groups of steel and hard alloys. The reliability of the results and the working efficiency of the obtained equations and models are supported experimentally. Their application in the technological process of design allows the true shape of the wire electrode to be calculated, which makes it possible to develop machining technology and the relevant patterns of motion of machine drives.

Keywords: wire electrical discharge machining, sparking rate, wire-electrode deflection, surface formation

DOI: 10.3103/S1068375519060073

INTRODUCTION

Beginning at the moment of their invention, electrospark machining and its branch wire electrical discharge machining (WEDM) developed step by step and firmly maintained their position among highly effective technologies that were used extensively in practice [1]. Many technical and technological problems have already been solved, and improvement still continues.

One urgent problem whose solution has been the subject of much research, is the ensurance of a required precision in the surface formation of workpieces, using a flexible wire electrode in WEDM. Electrospark machining is no longer considered a forceless process [2]. Instead, it is studied to understand which forces change the shape of the electrode and how they affect the precision of the machining.

The increasing significance of the power factors results from the two directions of the development of the modern WEDM. The first is the assurance of high precision in cutting thick 300-mm workpieces using batch production machines [3]. An increase in the distance between the fixation points of the wire electrode leads inevitably to the loss of its transverse rigidity. Second is an increase of up to 500 mm^2/min [4] in the manufacturing rate of WEDM [4], reached using high-intensity spark discharges, causing an increased power load on the electrode. All these together deviate the wire electrode from its rectilinear form, resulting in a loss of control over the surface formation, which can lead to overrunning the limits of the accuracy parameters required by precision parts.

ANALYSIS OF LITERARY DATA. AIMS AND TASKS OF RESEARCH

In the study of methods of electrical discharge machining using a plain wire electrode, many authors have devoted significant attention to the question of increasing the accuracy of the machining. The major primary errors considered by these authors included those conditioned by the geometrical precision of the machine drives. Errors can also result from wire vibrations in the guiders, from mistakes in the manufacture of the wire, and the presence of an interelectrode gap. They can be caused by inaccurate definition of coordinates of the basic surfaces, wire wear, temperature deformation, residual strains, and deflections of the wire electrode under the impact of the force of electrical discharges. The majority of these can be minimized, except for the most significant error, caused by the deflection of the wire electrode. This error remains incompletely solved. As a consequence, the error of the surface formation at a rough cut of a full removal can be 0.02–0.4 mm, depending on the technological conditions and the configuration of the shape being cut.

The task of increasing precision is divided into two parts, i.e., the definition of the deflection of the wire for certain conditions and the development of the compensation for the error.

The design engineers of the firm AGIE have offered an automatic online check of the form of a wire electrode (it is currently being used on their machines) as part of the AGIEPILOT system [5, 6]. The wire positioning sensor consists of two optical pairs placed in mutually orthogonal directions with the wire electrode in between. A collimated light beam passes past the electrode, reaching a self-focusing object lens, behind which are two fiber optics. The difference in their signal intensities is used to determine the electrode shift. The sensor is located between the upper guider of the wire electrode and the surface of the workpiece. The measurement is performed far from the zone of erosion, i.e., far from the place of maximum deflection. Therefore, the mathematical model of the elastic state of the wire under a transverse distributed load is used to recalculate the measured data relative to maximum deflection.

Later, developments in computational power and the appearance of the programming systems made it possible to use a more rational preliminary design of the WEDM technological process, up to its direct implementation. The problem of predicting the form of a wire electrode and its relevant surface formation in motion according to a preset contour has been solved in different ways.

Many researchers have applied statistical methods of multiparameter analysis of experimental data (ANOVA methods, Taguchi methodology), plotting regression equations and generalizing results to offer constructional designs of the following technological WEDM processes. In [7], the errors of surface formation are studied in the cutting of the external and internal angles with small rounding radii at the apex. A three-pass machining is used, and the first rough cut is noted to introduce the maximum error caused by the deflection of the wire electrode. After the following two finish passes, the error is reduced. The ratios between the value of the aperture of the angle, the radius at the apex, and the quantity of the remaining unutilized material were obtained using a pure geometrical model. The authors consider the results to be independent of the used metal material.

Statistical methods are also used in [8] to study electrical discharge machining of the angles of workpieces from the traditionally hard-to-machine alloy Monel 400, which is composed of nickel 67.4%, copper 29.24%, and other components. In [9], the authors point out the necessity for analysis of the impact of force on wire electrode, caused by spark discharges and changes when cornering. However, later, they adopted a simplified model of the electrode form in which they accept an equal deflection along the entire height of the cut and propose a purely geometric elliptic model of plotting a trajectory to cut the angles. As a result, they apply a generalized nonlinear regressive model to optimize the technological parameters to reduce error during the machining of the angles.

The authors of [10, 11] carried out ranging of WEDM parameters relative to the degree of influence on the error of surface formation in a cone cut (four-coordinate machining with high inclinations), using the systematization methods of the experimental statistical data. It was shown that at high deformations of the wire electrode, the determining role belongs to the geometrical parameters, namely, to a slope angle, workpiece thickness and mechanical parameters of the wire itself. The authors consider the WEDM technological parameters to have little significance, and further modeling is performed without close attention to their effects on the form of the electrode. A nonlinear model is used, based on the finite element method (FEM) to clarify the level of deformation of the wire electrode near the guiders. Experiments were conducted using the samples of tool steel and boron carbide, for which the machining modes differ by almost twofold, according to the energy parameters of the spark discharges. Obviously, the FEM model used accurately takes into account the statistic deformation at the deflected electrode during the widely spaced guiders under cone cutting conditions but does not catch changes in shape with a significant change of transverse electrode load from pressure of spark discharges.

Experimental studies using the Taguchi method, which includes 13 control factors at three levels, are described in [12]. A die steel with a 28-mm thick metal (0.85% C, 4% Cr, 6.25% W, 5% Mo, and 2% V) was machined, after being quenched and annealed. After a comparison of the dispersion and contribution levels for each of the control factors, it was found that the most significant reason for geometrical error caused by the deflection of the wire were the time of the pulse action, pause duration between the pulses, and the peak current of the pulse during the rough cutting. The sparking rate of the discharge determines the value of the side load on the wire electrode, which causes its deflection. It was also found that the rate of the rough cutting depends on change in the above parameters and is proportional to the level of energy supplied to the zone of machining and yielded during discharges. That is, the rate of cutting can serve as an index of the side load value on the electrode. Unfortunately, the authors did not provide the formulas that make it possible to quantify such a connection.

A later paper [13] describes the results of machining experiments of plates with various thickness made of the same die steel. Cylinders were cut out, the errors were measured, and, using the mathematical model developed by the authors, which connected the distributed load, the wire electrode deflection and the surface formation parameters on the circular movement of the curved electrode, the value of the force intensity of the spark discharges was calculated. It was found that $qt = \text{const} = 24.372 \times 10^{-3}$, where q (kG/mm) is the force intensity induced by the spark discharges, and t (mm) is the height of machining. The obtained ratio made it possible to calculate the intensity of forces, and, hence, electrode deflection for other heights of machining with similar to mentioned above experiment conditions.

The experimental results of the direct measurements of forces induced by spark discharges are presented in [2]. The dynamic forces were registered using piezoceramic transducers, and the interelectrode gap was controlled with the use of a laser interferometer. Two high-speed cameras with controlled delays for time synchronization with spark discharges allowed the development of gas bubbles in a dielectric liquid to be observed and the parameters of vibration and value of the electrode deflection induced by the action of the occurring forces determined. Although studies of the parameters of pulses of piercing electrical discharge machining have been done, the obtained regularities make it possible to understand the gist of the general physical processes of the appearance and development of forces associated with spark discharges in a liquid.

The deflection of the wire electrode can also be induced by the hydrodynamic forces of the jet of the working liquid, supplied into the interelectrode gap from the upper and lower rinsing chambers [14, 15]. Using computational dynamics (CFD) in an ANSYS commercial software package with FEM, the modeling of the deflection of the wire electrode and a comparison of the results with experimental measurements were carried out. An interesting dependence of the deflection of the electrode on the length of the cut groove was obtained. It was found that with an increase in pressure in the rinsing chambers, the evacuation of the erosion products out of the interelectrode gap becomes more efficient, but in this case, the wire electrode deflection is increased, which negatively affects the accuracy of the machining. On the other hand, with a decrease in the pressure, the deflection reduces and the removal of the erosion products impairs. This leads to a decrease in the cutting rate and even to wire breakage. Very important quantitative data are obtained on the distribution of the working liquid stream that initiates the deflection of the wire electrode. However, because it is necessary to use a powerful computational resource, the application of this method seems fairly problematic in the everyday practice of the engineering design of the technological WEDM processes.

The effect of electrostatic and electromagnetic forces that cause the deflection of the electrode was studied in [16]. The analysis of surface-formation error in the cutting of external acute angles from thin plates showed that the direction of the deflection of the angle edge bend depends on the composition of the machined material, whether aluminum or carbon steel. A formula is developed to estimate the contribution of the electromagnetic forces to the total effect on the wire electrode. This error has a substantial effect in machining very acute angles at small thicknesses of a block of metal.

The works of authors [17–20] are devoted to the development of a strategy of compensation of the errors in surface formation, caused by wire electrode deflection. The principles of WEDM control are clear – a decrease of the wire deflection and shaping errors, which can be obtained by reducing the cutting rate, but at the same time the productivity of the process decreases. The balance between the process rate and the precision of the surface formation is impeded by the problem of the definition of the real shape of the wire electrode still remains unsolved for the conditions of a particular technological process.

The aim of this work is to elaborate the experimental-calculation methods and the equations used to calculate the value of distributed external load, which affects the wire in cutting for particular groups of steels and hard alloys. This will allow us, at the stage of designing the technological process, to calculate the real shape of the wire electrode, and taking it into account, build the processing technology and the relevant trajectory of the machine tool drivers.

The research objectives.

(1) To develop the methods of determining the real shape of the wire electrode full removal cutting.

(2) To propose a mathematical model of the shape of the wire electrode under the action of the external load.

(3) To determine the level of hydrodynamic forces acting on the wire caused by the flow of flushing fluid using a model cell of the interelectrode gap (IEG) flushing system.

(4) To obtain the equations for calculation of the value of the distributed external load, which affects the wire in cutting particular groups of steels and hard alloys, using the results of measurements of the maximum deflections of the wire and the mathematical model of the shape of the wire electrode under an external load.

(5) To experimentally verify the validity of the obtained equation.

MATERIALS AND METHODS OF RESEARCH

Materials and Equipment Used in the Experiment

Study of the physico-technological parameters of the wire electrical discharge machining was carried out using a SELD-02 electrical discharge machine manufactured at the Scientific Production Association ROTOR (Cherkasy, Ukraine). The machine uses linear engines as drivers, which together with granite guiders and gas charged supports provide minimum movement error. The wire winding path was equipped with compensators, which, together with the V-shaped guiders minimized the vibrations of the wire electrode.

Two modes of GKI 300-200A rough-cutting generators were used. The pulse characteristics, namely, specified a pulse frequency of 22 kHz and a pulse duration of 3 μs, and current amplitudes at a load of 0.1 Ohm 170 and 250 A were registered. The longitu-

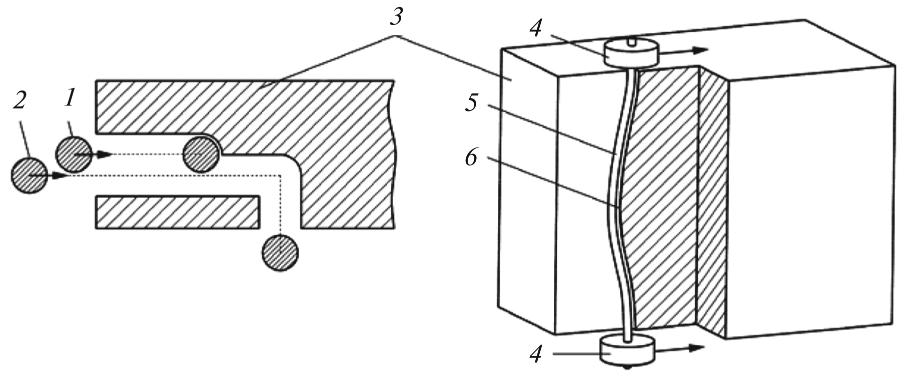

Fig. 1. Determination of real shape of deflections of wire electrode (scale not respected): (*1*) is the first rough cut with full removal; (*2*) is the second cut with displacement; (*3*) is metal workpiece; (*4*) are guiders; (*5*) is wire electrode; and (*6*) is the measured deflection line.

dinal tension of the wires varied in the range of 6–8 N, the pressures of flushing were 2.5×10^5 and 5×10^5 Pa.

Wire electrodes with diameters of 0.20 and 0.15 mm from Cobra Cut B (AGIE, Switzerland), with Fanuc-Norm (Matra) hard brass CuZn37 with a diameter of 0.15 mm from Fanuc (Japan), semisolid brass CuZn37 with a diameter of 0.25 mm from Electra LLC Meganom (Ukraine), and soft brass L63 were used.

The workpieces materials used for wire discharge machining of structural steel (steel 45), tool carbon steel (U8), and refractory low-alloyed steel (15XM). The thicknesses of the metal workpieces were 5, 10, 20, 30, 40, and 50 mm. The thicknesses of the hard-alloy (BK-8, BK-20) metal workpiecess were 5, 10, 20, and 30 mm.

Methods for Determining the Deflection of the Wire Electrodes

The experimental measurements of maximum deflections of the wire electrode were performed directly on the machines. The test cutting was performed with no power pulses in the IEG, and it was supplied with low-voltage, low probing pulses. Then, the flushing system was switched off, the working fluid was drained and the wire electrode was moved away from the machined surface of the workpiece until contact was lost between them, as registered by the moment of disappearance of the sparking discharges of the machine apparatuses. Here, the difference between the coordinates of the end point of the occurrence and the point of disappearance of the contact. The value of the maximum deflection was determined from the following expression:

$$f = j - e,$$

where e is the value of the interelectrode gap, and j is the difference between the coordinates of the point of occurrence and that of disappearance of the contact.

The value of e was determined on the machine by touching the walls of the groove being machined with the wire electrode and during the supply of low-level probing pulses on the wire.

Thus, with an error less than the sum of the errors of the measurement system of the machine and the diameter of the wire, the value of the maximum deflection of the wire electrode was measured.

The method of the definition of the full shape of the wire electrode from the top to the bottom through the cutting height was as follows (Fig. 1). First, rough cutting was done with full removal at a maximum spark discharge intensity in accordance with the chosen technological mode (point *1*). At a definite depth of cutting-in, the process was stopped. Then, the second cutting was performed with an offset aside, precisely at half the width of the cutting (point *2*), so that a part of the metal bulk was cut off. Thus, it became possible to measure the edge, which is a midway line of the first cutting. The coordinates of the line of deflections (point *6*) were taken using a DIP-3 two-coordinate measuring microscope. Then, a recount of the data for the shape of the wire electrode was performed, taking into account the interelectrode gap value. Optical guidance on the measured edge made it possible to determine the coordinates with an error of up to $\pm(1.0 + L/200)$ μm, where L is the measured size in mm.

Mathematical Model of the Wire Electrode Shape

To determine the wire electrode deflections in the general case in a four-coordinate WEDM, a mathematical model was used in which the electrode was presented in the form of a flexible wire (Fig. 2) that functions only when stretched, i.e., flexible rigidity is absent, and stretching tensions are always directed tangentially with respect to the wire.

The differential equation that describes the form of the wire electrode is as follows:

$$\frac{d^2y}{dz^2} = \frac{q(z)}{H_0}. \quad (1)$$

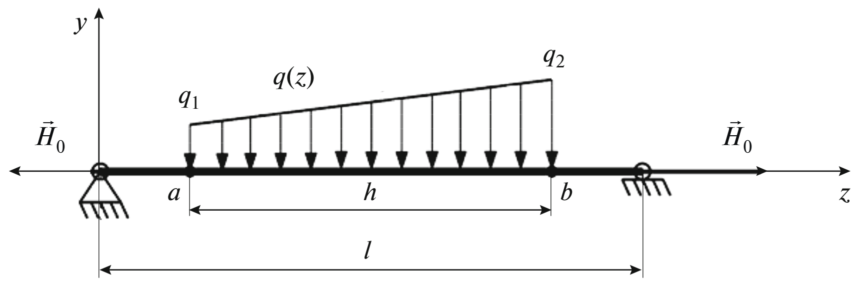

Fig. 2. Calculation scheme of deflections of wire electrode at different movement speeds of points (a) and (b): l is distance between points of wire fixation; h is height of workpiece; $\vec{H}_0$ is stretching tension of the wire; $q(z)$ is distributed cross section load.

The spatial-temporal distribution of the spark discharges justifies the view of their force of action as a distributed load, using the following expression:

$$q(z) = \begin{cases} 0, \ z < a; \\ q_1 + \dfrac{z-a}{b-a}(q_2 - q_1), \ a \le z \le b; \\ 0, \ z > b. \end{cases} \quad (2)$$

In particular, for $q_1 = q_2$ we obtain the case of a two-coordinate WEDM, when the wire electrode moves without deviation from the vertical position.

The solution for Eq. (1) with an account of load (2) is as follows:

$$y(z) = \frac{l}{2H_0}\left\{\frac{z}{l}\left[q_1((l-a)^2 - (l-b)^2) + \frac{q_2 - q_1}{3(b-a)} \times ((l-a)^3 - (l-b)^3)\right] - q_1((z-a)^2 - (z-b)^2) - \frac{q_2 - q_1}{3(b-a)}((z-a)^3 - (z-b)^3)\right\}, \quad (3)$$

where it is necessary to use $(z - a) = 0$, at $z < a$ and $(z - b) = 0$ at $z < b$.

Formula (3) makes it possible to calculate the deflection of the wire electrode for any arbitrary cross section.

The designed model was used as an inverse problem. Using the experimentally measured shape of the wire electrode and the mathematical model, we determined the functioning distributed transverse load for the specific technological conditions of the machining.

Experimental-Calculation Method for Estimation of Hydrodynamical Forces Induced by the Flushing Fluid Stream

Most engineers of the wire electrical discharge machines use coaxial flushing of the interelectrode gap to remove the products of erosion from the zone of machining and to intensify the cooling of the wire electrode. Different constructions of built-in nozzles are used to ensure the simultaneously injection of the hydraulic liquid from the bottom and from above, along the axis of the wire electrode. As a result, a transverse distributed force load appears, induced by the hydrodynamic resistance of the wire to the flushing fluid stream. The value of the load is determined by the rate of the transverse streamline motion around the wire and depends on the geometrical parameters of the cut groove and the pressure of the working liquid in the upper and lower shoulders of the machine hydrosystem.

A force load resulted from the decrease in the pressure ΔP between the front cutting surface and the back surface of the wire electrode. The losses in the pressure are determined using the Weisbach formula:

$$\Delta P = \xi \frac{\rho V^2}{2}, \quad (4)$$

where $\xi = \dfrac{33}{\text{Re}}$ is the coefficient of resistance of the rectangular gap, Re is the Reynolds number, V is the fluid stream velocity, and ρ is the liquid density.

The Reynolds number for the slit-type gap can be defined using the following formula:

$$\text{Re} = \frac{VC}{\mu}, \quad (5)$$

where $C = \dfrac{\delta h}{2(h+\delta)}$ is the ratio of the area of passage section to the wetted perimeter, δ is the minimum size of the cross section of the output of the working liquid from the interelectrode gap, h is the height of cutting, and μ is the kinematic viscosity of the working liquid.

Using (4) and (5), we find a rate of the stream of liquid around the wire electrode:

$$V = \frac{\Delta P \delta h}{33(h+\delta)\rho\mu}. \quad (6)$$

For the experimental determination of $\Delta P = P_1 - P_2$ we used the model cell of the flushing system (Fig. 3).

To measure the pressure, an IPDTs-89007 manometer was used, with limiting measurements from 0 to 10 kPa and an admissible error of ±0.07%.

Through the blocks of the measuring channels, the liquid working pressures P_1 and P_2 were registered in

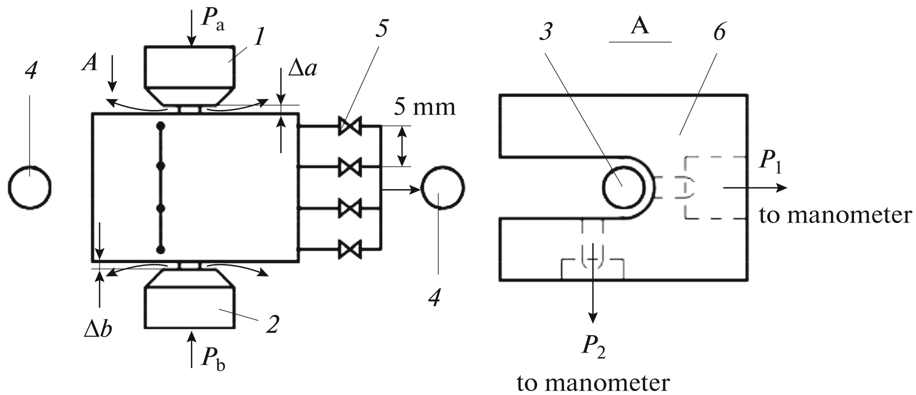

Fig. 3. Scheme of pressure measurement of working liquid along the length of the groove being cut; (*1*) is the upper flushing nozzle; (*2*) is the lower flushing nozzle; (*3*) is the wire electrode; (*4*) are manometers; (*5*) are measurement channel valves; (*6*) is the device frame; P_a, P_b are liquid pressures in the upper and lower flushing systems; P_1 and P_2 are pressures in the front part of interelectrode gap and at its output; and Δa and Δb are gaps between flushing nozzle and frame.

different cross-sections along the height of the groove being cut. Further, Eq. (6) enabled us to calculate the stream rate and consumption of the liquid that passes through the interelectrode gap.

For flushing pressure of $P_a, P_b \leq 8\times10^5$ Pa, the Reynolds number is always less than 2 × 10^5. The hydrodynamic resistance of the wire electrode can be calculated with the formula for a cylinder in a stream of liquid:

$$F_{\rm hydr} = C_x W \frac{\rho V^2}{2} = q_0 h, \tag{7}$$

where $W = dh$ is a characteristic cross section (maximum cross section of wire), d is the wire diameter, and C_x is the coefficient of resistance of a cylinder with an axis perpendicular to the stream, which is considered equal to 1.2 for the Reynolds numbers.

Hence, based on formulas (6) and (7) it is possible to determine the transverse distributed load q_0, that impacts the wire electrode:

$$q_0 = 0.6d\frac{1}{\rho}\left(\frac{\Delta P\delta h}{33(h+\delta)\mu}\right)^2. \tag{8}$$

RESULTS OF THE STUDY

These experimental studies are targeted at determining the relationship between the rate of the wire discharge machining V and the distributed load q, induced by the action of the electrical discharges. The experimental dependences in the process of cutting of different steels and hard alloys are shown in Fig. 4. Different rates were obtained during the first rough cutting in the machining of metal workpieces with different thicknesses. For the technological conditions of each experiment, the maximum deflection of the wire electrode was measured, and using formula (3), the calculation of the distributed load that caused the electrode deflection was performed.

The data obtained for the steels and hard alloys within the margin of error of 6% were approximated by the linear function (straight line *1,* Fig. 4):

$$q = kV + q_0, \tag{9}$$

for steels the approximation is

$$q_{st} = 0.953V + 0.025, \tag{10}$$

and for the hard alloys it is

$$q_{\rm ha} = 1.94V + 0.04. \tag{11}$$

The results of the experimental studies of the effects of the gap value between the flushing nozzle and the metal bulk for value ΔP are presented in Fig. 5. The measurements were performed at pressure at the nozzle outputs of $P_a = P_b = 5 \times 10^5$ Pa and $\Delta a = \Delta b$.

As is seen in Fig. 5, with the decrease in the gap to 0, the ΔP value, and hence, the rate of the flushing increase. However, in this case, the probability of the accuracy loss (and defect occurrence) is increased, resulting through displacement of the guiders, due to the contact forces of the mobile nozzle with the workpiece. Therefore, it makes sense to set the gap equal to $\Delta a = \Delta b$ = 0.02–0.05 mm, which allows the straightforward mechanical contacts between the nozzle and the workpiece to be avoided, as well as the substantial losses in the consumption of the working liquid through the interelectrode gap. From this point on, all of experiments were carried out at $\Delta a = \Delta b$ = 0.02–0.05 mm.

Another constructive option is the use of spring-loaded output parts of the nozzles, which completely lie on the surface of the workpiece.

The results of the measurements of the distribution of ΔP along the groove height for thicknesses of 20, 45,

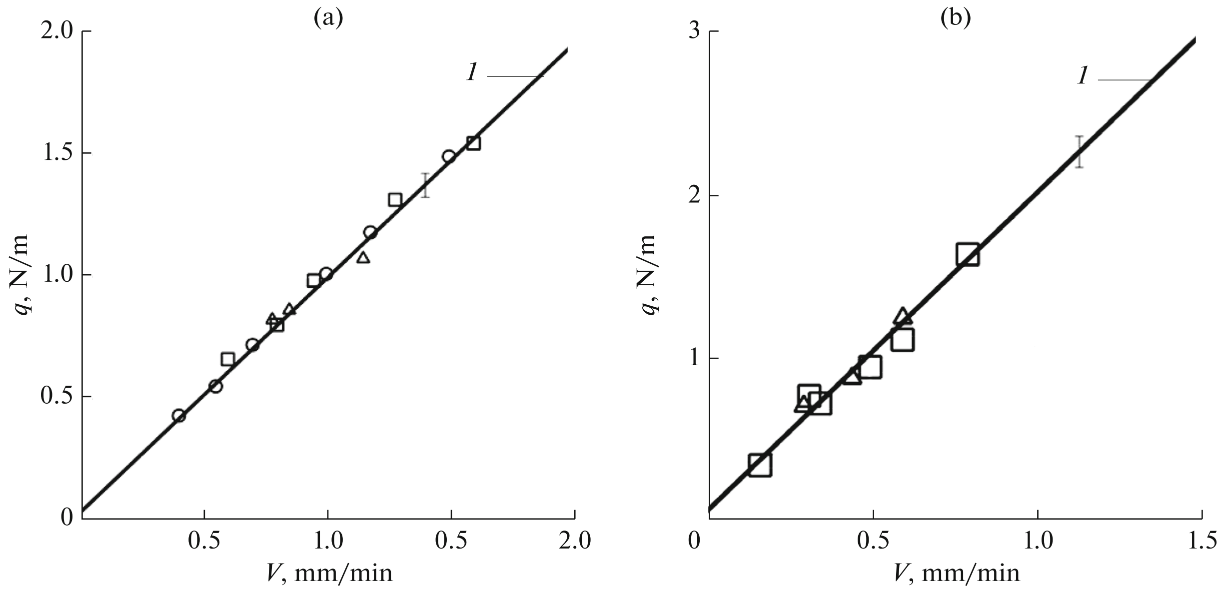

Fig. 4. Dependence of distributed load onto wire electrode with diameter of 0.2 mm on rate of cutting: (a) steels (○—steel 45, □—U8, △—15XM); (b) hard alloys (□—VK8; △—VK20).

and 100 mm and pressure in the machine hydrosystem of $P_a = P_b = 2.5 \times 10^5$ Pa and $P_a = P_b = 5 \times 10^5$ Pa are shown in Fig. 6.

In all experiments, a decrease in ΔP is observed from the lower and upper surfaces of the metal block to the middle of the groove. Hence, in these directions, there is a gradient of the rate of a cross flow around the wire electrode. A coaxial flushing under the same pumping from above and below forms in the sections close to the middle of the workpiece a stagnant zone in which the IEG flushing speed is minimal and the heat load on the wire electrode is maximum. The ΔP difference between the extremum and mid sections increases with the growth in thickness of the metal workpiece. This factor explains the decrease in efficiency of the cutting at $h > 50$ mm.

DISCUSSION OF THE STUDY RESULTS

The graph shown in Fig. 4a indicates that when machining steel 45 and various grades of steels with the same speeds, the values of distributed loads differ slightly. The same can be said about the hard alloys. Hence, there is no necessity to obtain dependence (9) separately for each steel and hard alloy because their distinctions are up to 2–6%.

This can be explained by the fact that the electrical discharge machinability (dependence of the intensity of erosion on the material properties) inside the groups of steels and hard alloys differs nonsignificantly. The electrical discharge machinability of hard alloys is about twice as bad as that of steels, which results in an increase of more than 100% in the electrohydrodynamic loads on the wire at the same rates of cutting. Taking into account that the electrical discharge machinability of the materials depends on their thermal-physical parameters (heat conductivity, thermal capacity, melting temperature, and evaporation temperature), the experimental results can be used to determine q in machining other steels and hard alloys, whose thermal-physical parameters do not differ by more than 10–15% from considered materials.

The authenticity of the latter assumption and operability of the models were experimentally verified during cutting a 30XGSA steel with thicknesses of 25 and 45 mm, as well as a VK10 hard alloy of 15 and 25 mm thick. The differences in thermal-physical constants of the above materials from those studied earlier reach 10%. It was found that the values of the maximum deflections of the wire electrode at the indicated

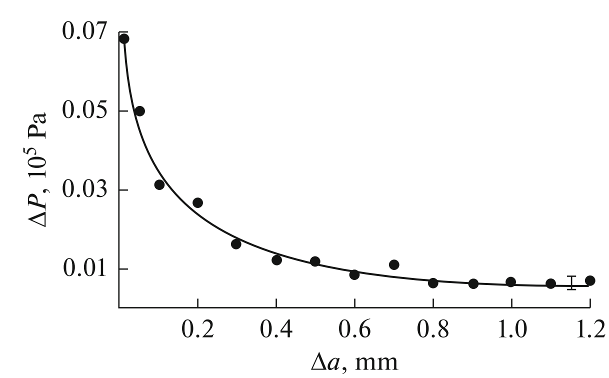

Fig. 5. Dependence of pressure drop of working fluid between front and rare surfaces of wire electrode from gap between nozzle and body of the part.

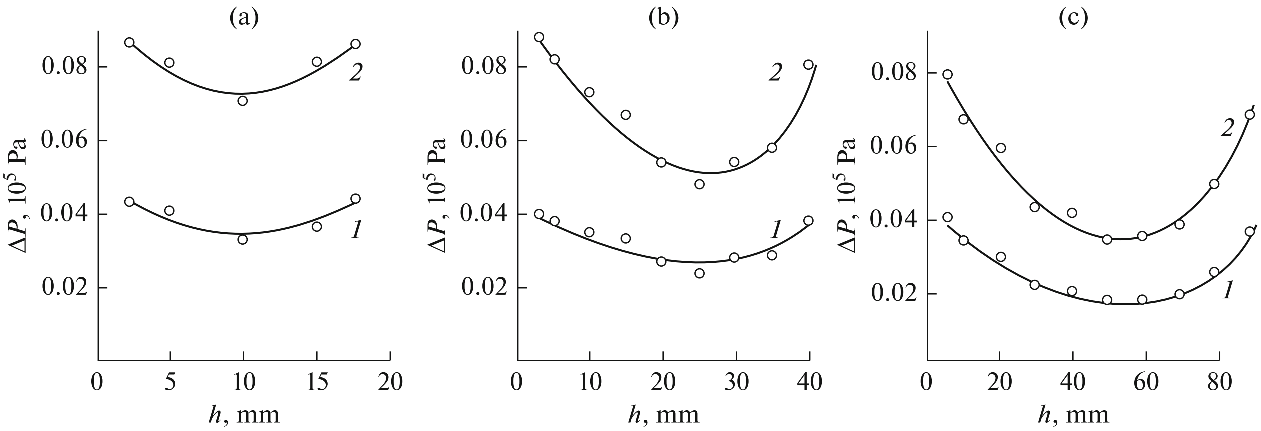

Fig. 6. Distribution of pressure drop of working liquid with respect to height for different thicknesses of metal blocks being cut: (*1*) $P_a = P_b = 2.5 \times 10^5$ Pa; (*2*) $P_a = P_b = 5 \times 10^5$ Pa; (a) $h = 20$; (b) $h = 45$; (c) $h = 100$ mm.

thicknesses differed from the calculated values by 0.006–0.015 mm (Table 1), which is 4–5%.

During the experiments, the measurement of the full shape of the wire electrode was also performed according to the abovementioned methods. It was found that the theoretically calculated shape in accordance with formula (3) and the experimentally measured coordinates of the deflections did not differ by more than 9% along the entire height of the groove cut.

The theoretical estimation of the value of the lateral load on the wire electrode, using formulas (4)–(8), and the values obtained resulting from the approximation of the experimental data from (10) and (11), show that the forces caused by the fluid flow are by an order of magnitude less than the load from the impact of spark discharges. The distinction between the last terms in (10) and (11) can be explained by the different thickness of erosion depositions on the side walls of the groove cut. When the hard alloy is machined more intensively, a reverse transfer of brass from the wire electrode onto the workpiece surface occurs, and the flow outlet cross section is significfntly narrowing IEG flushing.

Using the developed experimental-calculation methods makes it possible to determine the data bases for defining a precise shape of the wire electrode on machining other material groups, including the newly received alloys. These results serve as the basis for designing the WEDM technological process using the systems of automatized engineering. On designing the machining of complex-contour workpieces, the intensity variation of the discharges (pressure of discharged) must be taken into account when moving around the angles and along the arcs of circles. Using the quantitative geometrical parameters of the shape of the workpiece being obtained, we can purposefully apply the methods of compensation of the impact of the deflections of the wire electrode on the accuracy of machining and shape formation of the surface.

CONCLUSIONS

(1) Based on the complex of experimental and theoretical studies, an experimental-calculation technique was proposed, and equations were obtained to calculate the value of a distributed external load that affects the wire when cutting particular groups of steels

Table 1. Comparison of experimental and calculation values of the wire electrode deflection

Material	Thickness, mm	Wire diameter, mm	Maximum wire deflection, mm (calculation)	Maximum wire deflection, mm (experiment)	Deviation between experiment and calculation, %
30XGSA	25	0.2	0.160	0.152	5.2
30XGSA	45	0.2	0.213	0.207	2.8
VK-10	15	0.2	0.233	0.244	4
VK-10	25	0.2	0.293	0.308	4.8

and hard alloys. The results obtained allow us to calculate the true shape of the wire electrode at the stage of designing the technological process and, taking it into account, build the machining technology and corresponding trajectory of the machine drives.

(2) A mathematic model of the shape of a wire electrode under the influence of an external load was developed.

(3) A model cell for the IEG flushing system was created. By calculation and experimentally, the level of hydrodynamic forces acting on the wire and caused by the flow of flushing fluid was estimated.

(4) The experimental test showed that using the proposed experimental-calculation methods for cutting materials whose thermal-physical constants do not differ by more than 10% from those studied earlier, the theoretically calculated and experimentally measured coordinates of the deflections do not differ by more than 9% along the entire height of the groove cut.

REFERENCES

1. Stavitskii, B.I., *Iz istorii elektroiskrovoi obrabotki materialov* (The History of Electrospark Processing of Materials), Kharkov: Tsentr Inform, 2013.
2. Klocke, F., Garzón, M., Dieckmann, J., and Klink, A., *Prod. Eng.*, 2011, vol. 5, no. 2, pp. 183–190.
3. Takayama, Y., Makino, Y., Niu, Y., and Uchida, H., *Procedia CIRP*, 2016, vol. 42, pp. 623–626.
4. Sanchez, J., Rodil, J., Herrero, A., de Lacalle, L., et al., *J. Mater. Process. Technol.*, 2007, vol. 182, no. 1, pp. 574–579.
5. Dauw, D. and Beltrami, I., *CIRP Ann.*, 1994, vol. 43, no. 1, pp. 193–197.
6. Beltrami, I., Bertholds, A., and Dauw, D., *J. Mater. Process. Technol.*, 1996, vol. 58, no. 4, pp. 385–389.
7. Firouzabadi, H.A., Parvizian, J., and Abdullah, A., *Int. J. Adv. Manuf. Technol.*, 2015, vol. 76, pp. 447–459.
8. Selvakumar, G., Sarkar, S., and Mitra, S., *Proc. Inst. Mech. Eng., Part B*, 2012, vol. 226, no. 10, pp. 1694–1704.
9. Chen, Z., Huang, Y., Zhang, Z., Li, H., et al., *Int. J. Adv. Manuf. Technol.*, 2014, vol. 74, no. 5-8, pp. 917–929.
10. Sanchez, J., Plaza, S., Ortega, N., Marcos, M., et al., *Int. J. Adv. Manuf. Technol.*, 2008, vol. 48, no. 12, pp. 1420–1428.
11. Plaza, S., Ortega, N., Sanchez, J., Pombo, I., et al., *Int. J. Adv. Manuf. Technol.*, 2009, vol. 44, nos. 5–6, pp. 529–538.
12. Puri, A. and Bhattacharyya, B., *Int. J. Mach. Tools Manuf.*, 2003, vol. 43, no. 2, pp. 151–159.
13. Sarkar, S., Sekh, M., Mitra, S., and Bhattacharyya, B., *Precis. Eng.*, 2011, vol. 35, no. 2, pp. 339–347.
14. Okada, A., Konishi, T., Okamoto, Y., and Kurihara, H., *CIRP Ann.*, 2015, vol. 64, no. 1, pp. 233–236.
15. Kawata, A., Okada, A., Okamoto, Y., and Kurihara, H., *Key Eng. Mater.*, 2017, vol. 749, pp. 130–135.
16. Dodun, O., Gonçalves-Coelho, A.M., Slătineanu, L., and Nagîţ, G., *Int. J. Adv. Manuf. Technol.*, 2009, vol. 41, nos. 9–10, pp. 858–864.
17. Han, F., Zhang, J., and Soichiro, I., *Precis. Eng.*, 2007, vol. 31, no. 4, pp. 331–336.
18. Huang, Q.H., *Appl. Mech. Mater.*, 2014, vol. 536, pp. 1452–1455.
19. Hsue, W., Liao, Y., and Lu, S., *Int. J. Mach. Tools Manuf.*, 1999, vol. 39, no. 4, pp. 651–667.
20. Hsue, A.W.-J. and Su, H.-C., *J. Mater. Process. Technol.*, 2004, vol. 149, no. 1, pp. 117–123.

Translated by M. Baznat