Computer Modeling of Forming Surface by Sequential Wire Electrodischarge-Electrochemical Machining

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Abstract. The mathematical principles of computer modeling of the surface's formation process using the combined sequential technology of electrodischarge cutting and electrochemical machining by a wire electrode are developed. The data of computer modeling of complex surface formation processes using this technology, their analysis and the results of experimental verification are presented in this article. It is proved that the use of computer modeling methods allows to improve the surface forming accuracy and the quality of the parts` surface, which are manufactured by this modern promising technology.

Keywords: surface shape accuracy, wire electrical discharge machining, electrochemical machining, EDM/ECM combined process, wire-electrode deflection, ruled surface formation

1 Introduction

Wire electrical discharge machining (WEDM) has become one of the most popular processes for producing precise geometries in hard materials, such as those used in the tooling industry. Since it is recognized as a precision process, optimization of different aspects related to dimensional accuracy is a classic research topic [1].

For WEDM the problem is the reproduction of a given ruled surface by a non-rigid wire electrode, which is bent due to the forces caused by spark discharges. A particularly acute problem of surface forming error occurs when thick work-pieces are cut by a wire-cut EDM, the distance between the upper and lower guide is so wide that the wire is easily bent.

The researchers have proposed many effective strategies, including a hybrid computer-integrated system for the improvement of the corner cutting accuracy [2-4]. At the end of the processing of one corner`s side plane using different methods, the wire electrode is straightened and continues the processing of the second side plane. Unfortunately, such a two-stage strategy is not applicable when continuously cutting in circular interpolation mode along the circle arc. The bent wire electrode forms a barrel-shaped surface. The problem with barrel-shaped inaccuracy remains relevant, both for traditional WEDM and for high-speed WEDM, for workpieces with a thickness greater than 100 mm [5].

One of the latest cutting technologies, presented by Japanese researchers [6], is “High precision cutting for thick work-pieces”. The essence of the technology lies in the development of an optimum control of the discharge energy, paying attention to the wire bending. It can significantly reduce the wire bending and effectively improve the straightness of thick work-pieces. The straightness of 300 mm SKD11 work-piece is achieved to 7μm accuracy by cutting 3 times on the ROBOCUT machine. However, the reduction of the wire deflection in this case is achieved by decreasing the intensity of the discharges, and hence the loss of productivity and increasing of expensive processing time. Additionally, the entire heat affected zone of WEDM in the near-surface layers of a workpiece, which is usually detrimental, is not completely eliminated.

Significantly more promising is the use of the combined technology of sequential electrodischarge and electrochemical machining (ECM) with a wire electrode [7]. After roughing electrodischarge cutting, follow 1–2 passes with electrolyte feed to the processing area. The transverse forces do not act on the wire electrode, it remains straight and as a result of the anode dissolution, the surface of the part is aligned, the heat-affected zone is completely eliminated.

An actual task for the implementation of the proposed combined technology is the creation of mathematical methods for calculation support and modeling of the formation of ruled surfaces by a wire electrode. Computer simulation dramatically reduces the amount of experimental work and the accuracy degree can be acceptable for many applications.

The aim of the work is to develop and carry out testing of computer modeling methods to improve the accuracy of surface forming and surface quality of parts manufactured using the latest technology of combined electrodischarge and electrochemical machining with a wire electrode.

2 Experimental equipment, materials

Experimental studies of forming processes by electroerosive wire cutting and subsequent electrochemical machining with a wire electrode were carried out on an electrodischarge cutting machine SELD-02 (Ukraine) with computer numerical control (CNC) systems. The rough cutting mode of the generator GKI 300-200 A was used. Pulses` characteristics: the nominal pulse frequency 22 kHz, pulse duration 3 μs, current amplitude at load 0.1 Ohm 170 A. The longitudinal tension of the wire varied within 6 - 8 N, the pressure of the working fluid was $5 \cdot 10^5$ Pa. A 0.20 mm Cobra Cut B (AGIE, Switzerland) wire electrode of a solid brass CuZn37 was used. Pulse electrochemical treatment was carried out by the same electrode in a 1 M NaCl aqueous solution in a potentiostatic regime. Workpieces 40, 68, 100 mm height made of tool stamping steel X12Ф1 (analogue DIN X155CrVMo12-1).

Shape deviations of the fabricated surface were studied using the Coordinate Measuring Machine 3D CMM AXIOM CNC ABERLINK. The limit of permissible error is ± (1.8 + 0.4L/100) µm, where L, mm is the measured length. The software allows you to set the value of the deviations from the cylindrical shape of the obtained cloud of points. Surface microgeometry was studied using a TIME 3221 profilometer and DataView TIME3R Series software.

3 Methods

3.1 Mathematical principles of computer modeling of WEDM surface forming

For two-coordinate electroerosive cutting, the wire electrode is flexed due to the distributed transverse load caused by spark discharges along the entire height of the workpiece. The computational scheme for determining the shape of the wire electrode (Fig.1) is a special case of a mathematical model of the wire electrode shape in four-coordinate electroerosive machining given in [8]. The experimental-computational method for determining the transverse load *q(z)* is presented there, depending on the cutting regimes and the material being processed from the class of tool steels and solid alloys.

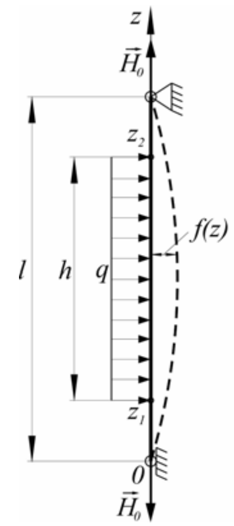

Fig. 1. The calculation scheme of wire electrode deflections: *l* – the distance between the nodes of the wire fixations; $h = z_2 - z_1$ – height of the machined part; $\overrightarrow{H_0}$ – longitudinal tension; $q = const$ – distributed transverse load

For our case, deflection magnitude of a wire electrode in an arbitrary section ($0<z<l$) is described by the formula:

$$f(z) = \frac{q}{2H_0}\left[\frac{z}{l}(l - z_1)^2 - \frac{z}{l}(l - z_2)^2 - (z - z_1)^2 + (z - z_2)^2\right], \quad (1)$$

where we state *(z – z1) = 0* at *z < z1* and *(z – z2) = 0* at *z < z2*.

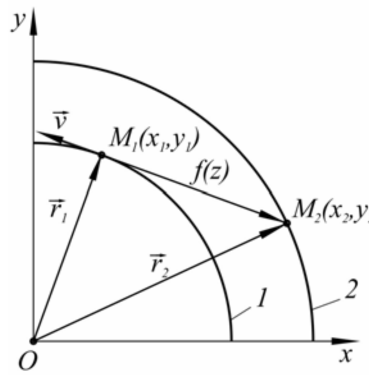

Fig. 2. Movement scheme of the points of the wire electrode: *1* – given movement contour of electrode fixation`s points; *2* – trajectory of the point of the electrode with a deflection *f(z)*

To determine the shape of the surface, which is formed by a deflected wire electrode while moving along the arc of a circle in space, consider the scheme of motion of individual points of the electrode (Fig. 2). Let the wire fixation nodes (point $M_1(x_1,y_1)$) moving along the arc of a given radius r_1 (program trajectory). Then point $M_2(x_2,y_2)$, which is at a height z of a wire electrode with a corresponding deflection $f(z)$, describes another arc of the radius r_2. Vector $\overrightarrow{M_1M_2}$ directed at a tangent to a circle at the point M_1 in the opposite direction of the velocity vector $\vec{v}$, then $\overrightarrow{M_1M_2}$ is perpendicular to the vector $\vec{r_1}$. Vector length $\overrightarrow{M_1M_2}$ is equal to $f(z)$. Then

$$r_2(z) = \sqrt{r_1^2 + f^2(z)}\,. \quad (2)$$

Or, in the form that is convenient for simulation, we obtain expressions for the coordinates of the point M_2 depending on the position in height z ($z_1<z<z_2$):

$$x_2(z) = f(z)\cdot\frac{y_1}{r_1} + x_1,\;\; y_2(z) = y_1 - f(z)\cdot\frac{x_1}{r_1}. \quad (3)$$

Thus, according to the established form of the wire electrode and taking into account the correction for half the cut width, which for WEDM consists of the wire electrode radius and the value of the interelectrode gap (IEG), the shape of the linear surface obtained as a result of the electrode movement along the arc section of the given trajectory is built.

3.2 Mathematical principles of computer modeling of wire ECM surface forming

The rate of anode dissolution, and hence the change of shape, depends on the density of the technological current on the surface of the part. For an electrochemical cell with the following configuration of electrodes, a cylindrical cathode – a cylindrical anode – the law of distribution must be established of the electric field strength in the IEG and the current density on the anode surface. The calculation scheme is presented in Fig.3. Using the method of conformal mappings of the complex variable function theory [9], we obtain the expressions for the intensity of the electric field:

$$E_x = A\left(\frac{x}{x^2+(y-a)^2} - \frac{x}{x^2+(y+a)^2}\right), \quad E_y = A\left(\frac{y+a}{x^2+(y+a)^2} - \frac{y-a}{x^2+(y-a)^2}\right),$$

$$E = \sqrt{E_x^2 + E_y^2}\,, \tag{4}$$

where $a = \sqrt{b^2 + 2bR}$, $b = \dfrac{\delta(\delta + 2r_0)}{2(\delta + r_0 + R)}$, $A = \dfrac{\varphi_1 - \varphi_0}{\ln p_1}$, $p_1 = \dfrac{a+b}{a-b} \cdot \dfrac{a+\delta-b}{a-\delta+b}$,

here R – radius of the cylindrical surface of the anode, r_0 – radius of the cathode, δ – value of the interelectrode gap, φ_0, φ_1 – potentials on the cathode and the anode, respectively.

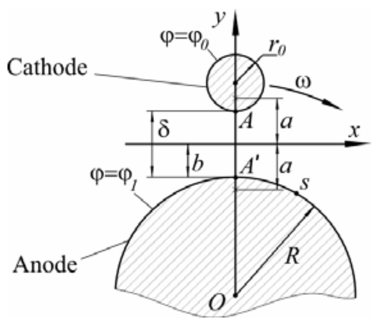

Fig. 3. Calculation scheme for determining the current density on an anode`s surface for a wire ECM

For small IEGs, typical for wire ECM, a simplified formula can be used:

$$E \approx A\frac{2a}{s^2 + a^2}\,, \tag{5}$$

where s – arc coordinate, which is calculated from point A' (Fig.3).

The maximum value of the electric field strength:

$$E_{\max} = E\Big|_{s=0} = \frac{2(\varphi_1 - \varphi_0)}{a \ln p_1}. \quad (6)$$

The maximum value of current density at the anode`s surface at the point *A'*:

$$j_{\max} = \frac{2\kappa(\varphi_1 - \varphi_0)}{a \ln p_1}, \quad (7)$$

where κ – specific electrolyte conductivity.

It is important to determine the thickness of the dissolved surface layer to simulate surface formation. To do this, consider the rotational motion of the wire cathode around the anode with the angular velocity ω (Fig. 3). The linear velocity of the cathode`s movement in a given trajectory is determined by the expression:

$$v = \omega \cdot (R + \delta + r_0). \quad (8)$$

Then the intensity of the electric field on the anode`s surface will take the form:

$$E = A\frac{2a}{(s - R\cdot\omega\cdot t)^2 + a^2}. \quad (9)$$

By Faraday's law, the depth of dissolution at the point *A'* during time *dt*:

$$d\Delta = K_v \eta j\Big|_{s=0} dt, \quad (10)$$

where K_v – coefficient of electrochemical dissolution of anode material, η – current ratio efficiency, j – current density.

After integrating (10) in the corresponding boundaries, we find the thickness of the dissolved layer in one processing run:

$$\int_0^{\Delta_m} d\Delta = 4K_v \eta \kappa A a \int_0^{t_k} \frac{dt}{(R\cdot\omega\cdot t)^2 + a^2}, \quad (11)$$

where $t_k = \pi/\omega$. Or

$$\Delta_m = 4K_v \eta \kappa A \frac{1}{R\omega} arctg(\frac{\pi R}{a}). \quad (12)$$

For potentiostatic pulse regime of ECM at $\varphi_1 = 0$, $\varphi_0 = -U$, U – voltage, we finally get:

$$\Delta_m = 4K_v \eta \kappa \frac{U}{R\cdot\omega\cdot\ln(p_1)} \frac{t_i}{t_n} arctg(\frac{\pi R}{a}), \quad (13)$$

where t_i – pulse on-time, t_n – period of pulses.

After the electroerosive cutting on the arc of radius *R* with the deformed wire electrode, the resulting surface will have a convexity in the middle of the workpiece along the *z* axis (Fig. 4). In the case of the subsequent ECM using nondeformed wire electrode, minimal and maximal IEGs will be δ_1 and δ_2, respectively. From the formulas` analysis (4), (7), (13) it follows that the intensity of the electric field, the current density, and, as a result, the intensity of the anode dissolution increases with the decrease of IEG. Therefore, in the middle of the workpiece material removal will be bigger and the process will tend to leveling the surface in height. That is, when wire moves in a circle with radius $R + \delta + r0$ there will be removed thicknesses Δ_{m1}, Δ_{m2}, considering $\Delta_{m1} > \Delta_{m2}$, as $\delta_1 < \delta_2$.

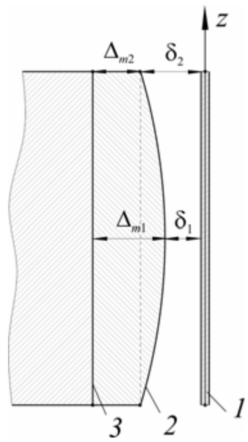

Fig. 4. Surface leveling using ECM after WEDM: *1* – wire electrode; *2* – distorted profile of the workpiece`s surface; *3* – leveled generating line of workpiece`s surface

A convex surface will become flat if equality is satisfied:

$$\delta_1 + \Delta_{m1} = \delta_2 + \Delta_{m2}\ . \quad (14)$$

We find the thickness of the dissolved layer in accordance with (13), then formula (14) will take form:

$$\delta_1 + \frac{A_1}{v} = \delta_2 + \frac{A_2}{v}\ , \quad (15)$$

where $A_1 = 4K_v \eta \kappa \frac{U}{\ln(p_1)} \frac{t_i}{t_n} arctg(\frac{\pi R}{a_1})$, $A_2 = 4K_v \eta \kappa \frac{U}{\ln(p_2)} \frac{t_i}{t_n} arctg(\frac{\pi R}{a_2})$.

From (15) we find the wire cathode velocity in a given trajectory for leveling the surface in the process of anodic dissolution:

$$v = \frac{A_2 - A_1}{\delta_1 - \delta_2}. \quad (16)$$

4 Results and discussion

Based on the mathematical dependences obtained, a series of computational experiments on computer simulation of surface forming processes using the WEDM and ECM with a wire electrode with the experimental verification of individual results was performed using the Mathcad package. Computational experiments have shown that the wire electrode deflection is significantly increased with increasing distance between fixation points – electrode guides. The parameter l is included in (1) at the power 2. This explains the emergence of the unacceptable surface formation error problem in the processing of thick parts.

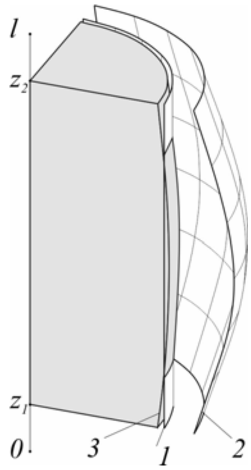

Fig. 5. The result of the surface formation by the combined technology: *1* – given cylindrical surface; *2* – convex surface after WEDM; *3* – the surface is formed as a result of ECM

Computer modeling of shaping of ruled surfaces (Fig. 5) using WEDM by deformed wire electrode during cutting in circular interpolation regime revealed a significant dependence of the error from the trajectory arc radius. The determinant factor is the relationship between the thickness of the workpiece and the magnitude of the arc radius – the generating line of the cylindrical surface.

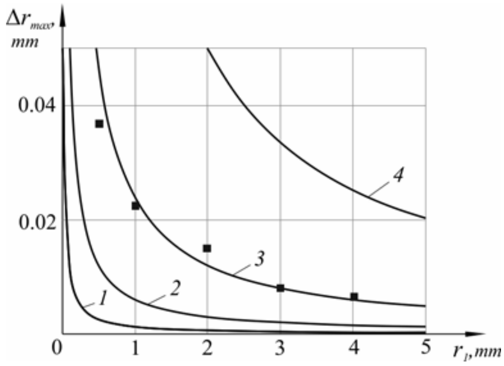

Fig. 6. Dependence of the maximum error of the surface forming of cylindrical surface Δr_{max} from the arc radius of program trajectory r_1 for different thicknesses of the workpiece: *1* – 40 mm, *2* – 68 mm, *3* – 100 mm, *4* – 150 mm, ■ – experimentally measured error values

Fig. 6 shows the graphs of the dependence of the maximum errors magnitude of the cylindrical surfaces formation on the arc radius of the program trajectory, on which the wire electrode with a deflection moves in the process of WEDM. Using computer simulation, it was found that when cutting cylindrical parts from a 40 mm thick workpiece, the error of surface reproduction due to the wire electrode deflection does not exceed the requirements for the accuracy of cutting for most technological cases (curve *1*, Fig.6). When cutting parts from a 68 mm thick workpiece, the formation error of the cylinders with a radius less than 0.5 mm becomes significant (curve *2*). Curve 3 shows that surface formation error, due to the wire electrode deflection, will exceed 20 microns when cutting a cylindrical part with a radius less than 1 mm in diameter. With an increase in the thickness of the workpiece, the formation error will increase dramatically. The theoretically calculated curve *4* for the thickness of the workpiece of 150 mm, shows, that for radii of 5 mm and less, error becomes unacceptably large.

The following simulation is performed for the aforementioned workpiece materials and WEDM cutting regime. Experimental verification of computer simulation with the coordinate-measuring machine control of the convexity of the obtained cylindrical surfaces, confirmed the satisfactory accuracy of the model. The maximum measured difference between the results of the computational and physical experiment does not exceed 8% (Fig.6).

For other WEDM technological regimes, it is advisable to use the method of determining the power factors influencing the wire electrode described in [8] and to conduct a similar simulation according to the proposed method.

The task of the next stage of computer simulation of the cylindrical surface aligning process using the wire ECM technology is based on a reasonable choice of the amplitude-time parameters of the pulsed current and the velocity of the electrodes` movement along the trajectory. Theoretical calculations, simulations and particular experimental studies have shown that already at the beginning, anodic dissolution predominantly aligns the difference between the convex part in the middle of the height of the cylindrical surface and the less convex regions from above and below (Δ_{m1} and Δ_{m2} respectively, Fig. 4). Then, with the time of dissolution, the difference between Δ_{m1} and Δ_{m2} decreases, and more intense removal of the thickness of the entire surface layer becomes more predominant than the surface leveling in terms of the height of the workpiece. Indeed, from formulas (4), (13) it can be seen that the dissolution rate depends on the intensity of the electric field, which is higher on the humps. Over time, the humps become smaller and the unevenness of the distribution of tension is leveled. In practice, this means that it is not necessary to continue the process until the full alignment of the surface, but it is advisable to stop when achieving the required precision of reproduction of geometric parameters (Fig.5). This once again proves the importance of computer simulation in the design process of the combined technology. Its use allows to predict the magnitude of the surface formation error obtained after WEDM and, accordingly, the amplitude-time parameters of the pulsed current and the velocity of the electrode movement along the trajectory to reduce deviation level to the acceptable result using subsequent ECM with a wire electrode.

Increasing the intensity of the predominant dissolution of humps is possible by reducing the gap between the wire electrode and the surface of the part. The electric field strength concentration increase becomes more noticeable on the humps compared with the caverns. However, setting the IEG of less than 0.1 mm is not allowed due to disruption of a uniform electrolyte flow throughout the height of the part. The uneven and insufficient renewal of the electrolyte in the intercolectrode space leads to a decrease in the current efficiency (η in formulas (10-13), (15)), which significantly influences surface shaping and, accordingly, the accuracy of its modeling.

In addition to increasing accuracy, due to electrochemical machining with a wire electrode, surface quality is also improved. The heat affected zone, obtained due to spark discharge, is completely removed. Surface roughness is reduced. Experimentally obtained decrease in roughness from Ra 2.7 – 3.2 μm after WEDM to Ra 0.65 – 1.2 μm after the ECM stage. It should be noted that the possibilities of improving surface properties by finishing electrochemical machining, in particular, reducing the surface roughness, are not limited to the results obtained in this paper. By choosing the amplitude-time characteristics of pulses, the electrolyte composition, modern technologies of electrochemical surface polishing achieve even more significant results [10,11].

5 Conclusion

1. There are created mathematical principles of computer simulation of the process of surface forming using combined WEDM and ECM with a wire electrode.

2. The implemented complex of computational experiments allowed broadening the idea of complex surface forming processes using the technology of a combined sequential WEDM and ECM with a wire electrode. Experimental verification of computer simulation results confirmed the adequacy of the proposed mathematical models.

3. Usage of computer simulation technologies allowed to improve the shaping accuracy and surface quality of the parts manufactured with the combined technology WEDM and ECM with a wire electrode.

4. The obtained results are an element of the scientific basis for the further development of the modern promising technology.

References

1. Sanchez, J.A., Plaza, S., Lopez de Lacalle, L., Lamikiz, A.: Computer simulation of wire-EDM taper-cutting. International Journal of Computer Integrated Manufacturing, vol. 19(7), pp. 727-735 (2006) doi:10.1080/09511920600628855
2. Sanchez, J.A., Lopez de Lacalle, L.N., Lamikiz, A.: A computer-aided system for the optimization of the accuracy of the wire electro-discharge machining process. International Journal of Computer Integrated Manufacturing, vol. 17(5), pp. 413-420 (2004) doi:10.1080/09511920310001626590
3. Han, F., Zhang, J., Soichiro I.: Corner error simulation of rough cutting in wire EDM. Precision engineering, vol. 31(4), pp.331-336 (2007) doi:10.1016/j.precisioneng.2007.01.005
4. Chen, Z., Huang, Y., Zhang, Z., Li, H., Ming, W., Zhang, G.: An analysis and optimization of the geometrical inaccuracy in WEDM rough corner cutting.

The International Journal of Advanced Manufacturing Technology, vol. 74(5-8), pp.917-929 (2014) doi:10.1007/s00170-014-6002-5
5. Deng, C., Liu, Z., Zhang, M., Ji, Y., Pan, H.: Minimizing drum-shaped inaccuracy in high-speed wire electrical discharge machining after multiple cuts. The International Journal of Advanced Manufacturing Technology, pp. 1-11 (2019) doi:10.1007/s00170-018-3068-5
6. Takayama, Y., Makino, Y., Niu, Y., Uchida, H.: The Latest Technology of Wire-cut EDM. Procedia CIRP, vol. 42, pp. 623-626 (2016) doi:10.1016/j.procir.2016.02.259
7. Osipenko, V.I., Plakhotny, A.P., Denisenko, A.Yu.: Improved methodology for calculating the processes of surface anodic dissolution of spark eroded recast layer at electrochemical machining with wire electrode. Pratsi Odeskoho politekhnichnoho universytetu, vol. 1(43), pp.55-60 (2014)
8. Osypenko, V., Plakhotnyi, O.: Determination of force factors influencing surface forming in wire electrical discharge machining. Elektronnaya obrabotka materialov, vol. 54(6), pp.9-18 (2018) (in Russian) doi: 10.5281/zenodo.1968973. The English version of the journal: Surface Engineering and Applied Electrochemistry.
9. Zhytnykov, V.P., Zaitsev, A.N.: Pulse precision electrochemical machining. Mashynostroenye, Moscow (2008) (in Russian).
10. Taylor, E.J., Inman, M.: Electrochemical Surface Finishing. The Electrochemical Society Interface, vol. 23(3), pp. 57-61 (2014) doi:10.1149/2.F05143if
11. Yang, G., Wang, B., Tawfiq, K., Wei, H., Zhou, S., Chen, G.: Electropolishing of surfaces: theory and applications. Surface Engineering, vol. 33(2), pp. 149-166 (2016) doi:10.1080/02670844.2016.1198452