Modeling Electrical Discharge Machining of Deep Micro-Holes by Rotating Tool-Electrode

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Abstract. In order to improve the machining characteristics of electrical discharge machining of deep micro-holes, rotational electrodes have been widely used. This paper is devoted to the theoretical and experimental investigation of the process of evacuation of debris particles from the interelectrode gap during electrical discharge machining of deep micro-holes. Mathematical modeling of hydrodynamic processes in the interelectrode gap is carried out on the basis of numerical solution of the equations of motion of incompressible viscous fluid, which allows one to estimate the influence of the shape and size of the tool-electrodes and their rotation on the evacuation of debris particles from the interelectrode gap. It was found that the use of tool-electrodes with a non-circular cross section enables one to accelerate the evacuation of debris particles. An experimental study of the process of electrical discharge machining of deep micro-holes is performed, and the simulated results are compared with the experimental data.

Keywords: Micro-hole · Electrical discharge machining · Rotating tool-electrode · Debris particles · Simulation

1 Introduction

Electrical discharge machining (EDM) is an effective method of machining hard materials, producing complex-shaped surfaces, and holes with various cross sections [1–3]. Unlike the mechanical machining, in the case of EDM, the material is removed from the workpiece surface with no force effect on the workpiece. This enables one to machine low-rigid workpieces and to form the elements with a high aspect ratio. EDM is widely used for the production of various micro-objects, and, in particular, micro-holes. Thus, according to SCOPUS over the past three years, the ratio of articles devoted to micro-EDM to all articles devoted to EDM is almost 50%.

EDM is a widely used method for machining deep micro-holes. However, with an increase of the micro-hole depth, the produced discharge debris particles cannot be removed from the interelectrode gap (IEG) quickly enough. A localized discharge or short circuit can arise leading to difficult machining [4–7].

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The productivity of EDM of the deep micro-holes under fixed working conditions directly depends on the intensity of the evacuation of debris particles from IEG. Since it is very difficult to organize the pumping of the dielectric fluid through the narrow IEG during EDM of micro-holes, the evacuation is carried out in a natural way, which is based on an electric discharge. After an electric discharge at the tip of tool-electrode, vapor-gas bubbles almost immediately fall into the vertical side of IEG, where they rise up by the lifting Archimedean force. At the same time, the upward moving vapor-gas bubbles carry with them dielectric fluid and erosion products, creating a flow. Since solid products in the studied process are microparticles ranging in size from several micrometers to several nanometers, the mechanism for their removal from the IEG is based on the flotation method, when microparticles are captured by the wall of the gas bubble. Natural evacuation of debris particles from IEG is not sufficient for a stable flow of the process. In order to improve EDM performance of holes machining, the removal efficiency of the discharge debris particles from narrow interelectrode gap must be improved. At present, many methods have been adopted to promote the removal efficiency of the discharge debris particles, such as pumping of dielectric fluid [8–10], electrode jump motion [11], electrode ultrasonic vibration [12, 13], electrode rotation [7, 14, 15], and their various combinations [3–6].

When using the flow of dielectric fluid requires the use of tubular electrodes-tools [8], through which the working fluid is pumped under high pressure. However, when machining of deep micro-holes (conventionally referred to holes with a diameter of less than 0.2 mm) there is a problem of manufacturing tubular electrodes.

The positive effect of ultrasonic vibrations is due to the following factors: (a) decrease in the diameter of vapor-gas bubbles; (b) increase in the number of vapor-gas bubbles and speed of their movement in the lateral IEG [12]. However, the use of tool-electrode vibration is not always appropriate. For example, if the machining of deep holes (up to 5 to 8 diameters), when the evacuation of debris particles from IEG is hampered, the vibrations may reduce the performance, because the periodic change of IEG reduces the number of normal discharges due to the increased number of the short-circuit pulses. Especially strongly this phenomenon is manifested during EDM at small gaps and large amplitudes of vibration.

Rotating tool-electrodes are widely used in EDM in order to improve the evacuation of debris particles from the treatment area [7, 14, 15]. The simplest tool-electrode for EDM of micro-holes has a cylindrical shape. When using a cylindrical electrode, it is possible to ensure stable hole processing only at a rather low depth. The rotation of the electrode allows to use tool-electrodes with non-circular cross section [16–20] for hole producing. The use of such electrodes can increase the amount of interelectrode space and thereby significantly facilitate the evacuation of debris particles. Therefore, the using of electrodes with a non-circular cross section (Fig. 1) provides the capability of producing micro-holes with a large aspect ratio.

The experimental study of the effect of rotation and cross-sectional shape on the efficiency of EDM is very difficult, so methods of mathematical modeling are widely used [21–24]. In view of the great complexity of the physical processes occurring in EDM, when modeling the evacuation of debris particles, approximate models are used

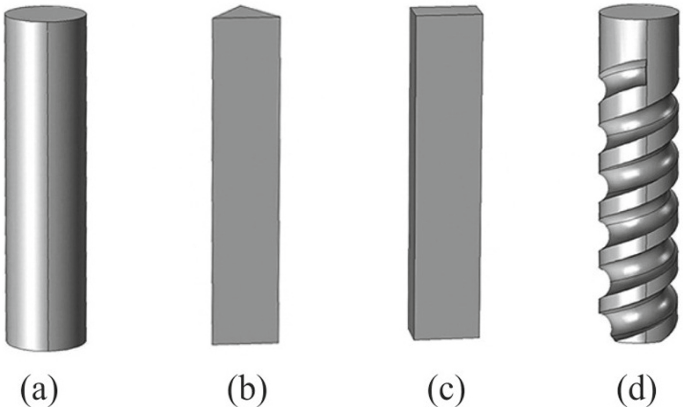

Fig. 1. Tool-electrodes various cross sections for EDM deep micro-holes: **a** cylinder; **b** triangular; **c** rectangle; **d** with spiral grooves.

that take into account only the most significant processes. Therefore, the simulation results require experimental confirmation.

This work is devoted to the theoretical and experimental study of EDM of deep micro-holes to assess the impact of the shape and size of the tool-electrode and the working conditions on the evacuation of debris particles from the interelectrode gap to ensure the possibility of improving the technological performance and the quality of the deep micro-holes.

2 Mathematical Model

As a mathematical model to describe the flow of dielectric fluid in the interelectrode space, which is a region bounded by the bottom and side surfaces of the micro-hole and the surface of the rotating tool-electrode, we will use the equations of motion of incompressible viscous fluid and the continuity equation [25]:

$$\rho\left(\frac{\partial u}{\partial t} + u \cdot \nabla u\right) = -\nabla p + \mu \Delta u + F_b \tag{1}$$

$$\nabla \cdot u = 0 \tag{2}$$

where u is the velocity vector of fluid motion; p is the pressure; ρ is the density of the dielectric fluid; μ is the dynamic viscosity of the dielectric fluid; ∇ is a vector differential operator; Δ is the Laplace operator; t is the time; F_b is the body force.

The debris particles in the interelectrode space were affected by the dielectric fluid, and their motion followed Newton's second law. The motion equation for the debris particles is as follows:

$$m_p \frac{\partial v}{\partial t} = F_D + F_g + F_{ext} \tag{3}$$

where m_p is the particle weight; v is the particle velocity; F_D is the drag force; F_g is the gravitational force; and F_{ext} is any other external force.

The drag force is determined as follows:

$$F_D = \frac{m_p}{\tau_p}(u - v) \quad (4)$$

where τ_p is the particle velocity response time.

When the relative Reynolds number between the particles and fluid is small, as is the case here, the particle velocity response time can be written as

$$\tau_p = \frac{\rho_p d_p^2}{18\mu} \quad (5)$$

where ρ_p is the particle density; d_p is the particle diameter.

During machining, the debris particles are formed at the bottom of the hole, which go into the gap between the side surface of the hole and the tool-electrode and rise up under the action of lifting Archimedean force:

$$F_g = m_p \frac{\rho_p - \rho}{\rho_p} g \quad (6)$$

where g is the gravitational acceleration.

The solution of the equations of the mathematical model (1)–(6), supplemented by the corresponding initial and boundary conditions allows to determine the distribution of hydrodynamic velocities of the dielectric fluid and the trajectories of the debris particles.

3 Results and Discussion

3.1 Results of Modeling

The Comsol was used for numerical simulation. On the basis of the results of preliminary experimental studies, the dimensions of the micro-hole (diameter and depth), as well as the shape and size of tool-electrode were set. The scheme of the computational domain is shown in Fig. 2.

When modeling, the surface of the tool-electrode rotates relatively to the hole axis. To ensure satisfactory accuracy of the solution, a finite element mesh with an optimal mesh element size of 50 μm is formed in the computational domain (Fig. 2c, d).

In the calculations, the rotation frequency of the electrode-tool was taken to be n = 3000 rpm. On the surface of the outer cylinder (the surface of the hole) the no-slip boundary condition is applied, and on the end surfaces—sliding of the liquid without friction. The free debris particles uniformly distributed over the end surface are given.

The simulation results show that the highest flow rate of dielectric fluid is observed in the lateral gap (Fig. 3). There is also a local increase in the velocity of the dielectric fluid between the side surfaces of the electrode-tool and the machined hole.

The results of modeling the motion of debris particles in IEG during EDM with the rotating electrode showed that the shape of cross section of tool-electrode significantly

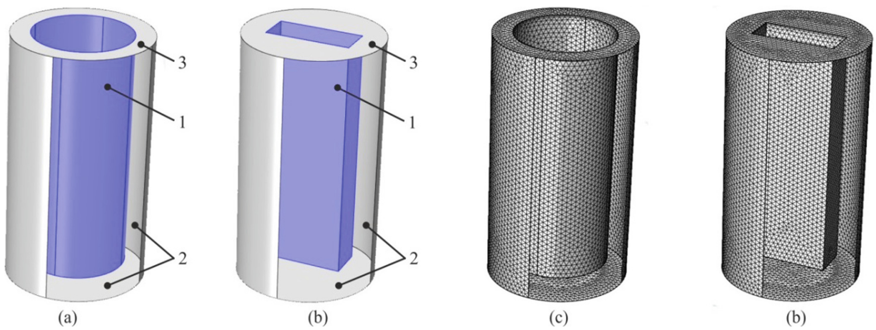

Fig. 2. Scheme of the computational domain and finite element mesh: **a**, **b** computational domain; **c**, **d** finite element mesh; **a**, **c** cylindrical tool-electrode; **b**, **d** rectangular tool-electrode; (1) a rotating tool-electrode; (2) the fixed surface of the hole; (3) boundary wall.

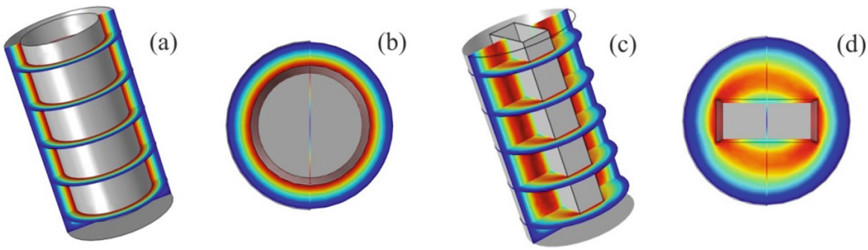

Fig. 3. Distributions of the dielectric fluid velocity module at EDM by electrodes of different shapes: **a**, **b** cylindrical; **c**, **d** rectangular.

affects the evacuation of debris particles. In particular, for the cylindrical tool-electrode the free space does not change over time (Fig. 4), therefore, the particles move only in this narrow gap. Figure 5 shows that, when rotating rectangular tool-electrode, debris particles move in free space, which varies over time. Thus, in comparison with the cylindrical electrode, the rectangular tool-electrode can significantly improve the conditions for the evacuation of debris particles from the treatment area through the lateral gap between the tool-electrode and the hole surface. EDM technology for producing deep holes through the use of sheet tool-electrode was proposed and implemented.

3.2 Experimental Studies for Model Validation

Experimental studies of the effect of profile tool-electrodes on the performance of EDM with rotating tool-electrode were carried out on the experimental setup (Fig. 6) at room temperature 20 ± 2 °C. For experimental studies of electrical discharge machining were used: aluminum sheet as workpiece; copper wire with circular (diameter 1 mm), and square (0.7 × 0.7 mm) cross section as tool-electrode; packages of high-frequency pulses with pulse duration in the package $t_{on} = 2.5$ μs; pulse amplitude $U_0 = 80$ V; the number of pulses in the package $N = 4$ (Fig. 7); kerosene was used as a working fluid. The conditions under which the experiments were carried out are presented in Table 1.

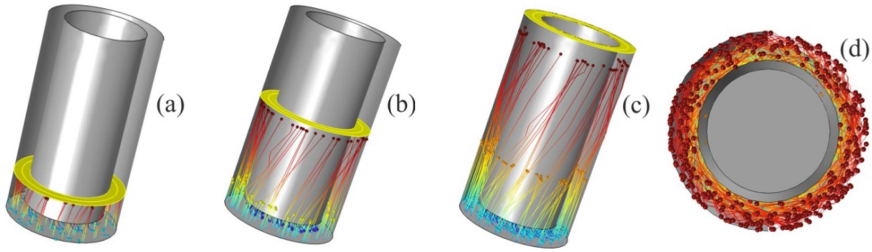

Fig. 4. Debris particles trajectories in IEG during EDM by rotating cylindrical electrode at various time: **a** t = 20 μs, h = 0.5 mm; **b** t = 35 μs, h = 1.4 mm; **c** t = 47 μs, h = 2.5 mm; **d** t = 100 μs.

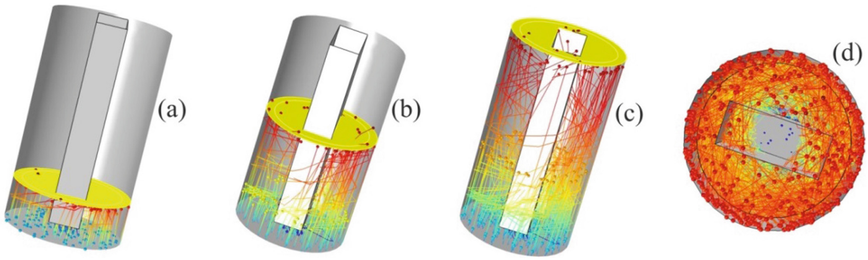

Fig. 5. Debris particles trajectories in IEG during EDM by rotating electrode with rectangular cross-section at various time: **a** t = 20 μs, h = 0.5 mm; **b** t = 35 μs, h = 1.4 mm; **c** t = 47 μs, h = 2.5 mm; **d** t = 100 μs.

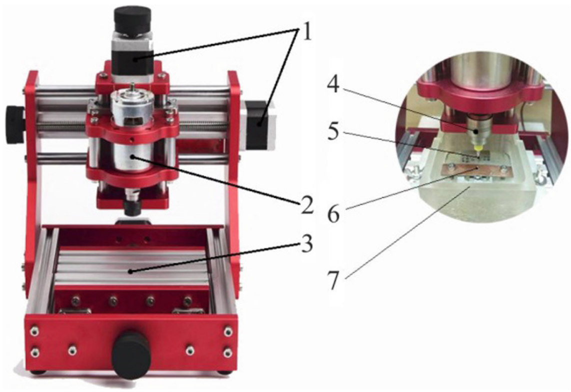

Fig. 6. Experimental setup for micro EDM: (1) drives the z- and x-axis; (2) the rotational drive of tool-electrode; (3) table; (4) collet chuck; (5) tool-electrode; (6) workpiece; (7) bath of dielectric fluid.

As a result of experimental studies micro-holes in EDM with a rotation of tool-electrode were obtained (Fig. 8).

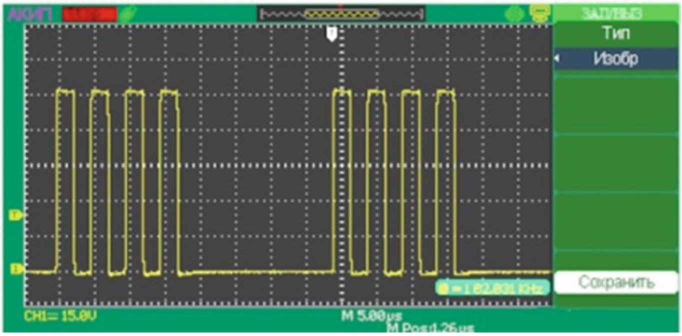

Fig. 7. Waveforms of voltage pulse packets.

Table 1. Basic parameters that ensure stable EDM-drilling of micro-holes in aluminum (electrode diameter is 1 mm).

EDM parameters	Value
Current I, A	0.5
Open circuit voltage U_0, V	80
Discharge voltage U_{gap}, V	40
Pulse duration t_{on}, μs	2.5
Puase duration t_{off}, μs	2.5
Number pulses in packet N	4

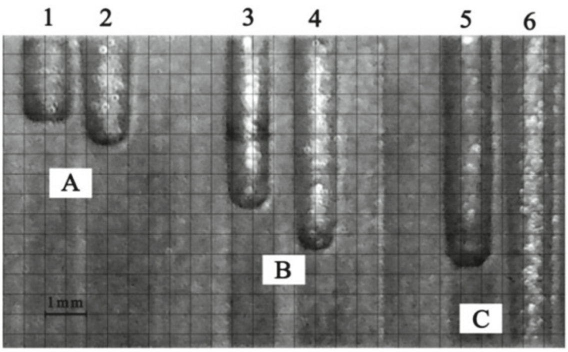

Fig. 8. Longitudinal cross sections of micro-holes obtained by EDM with rotation of tool-electrode: (1, 3, 5) cylindrical electrode; (2, 4, 6) rectangular electrode; **A** at t = 2.5 min; **B** at t = 5 min; **C** at t = 8.5 min.

4 Conclusion

As a result of the research, it was shown that the performance of electrical discharge machining using the rotating rectangular tool-electrode is much higher than using the rotating cylindrical electrode. Thus, the use of electrodes with a non-circular cross section allows to improve the conditions of evacuation of debris particles by increasing the volume of interelectrode space filled with dielectric fluid, reducing the hydrodynamic resistance. The comparison of the results of modeling and experimental data shows that they are in good agreement.

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