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Flow Field Simulation and Experimental Investigation of Ultrasonic Vibration Assisted EDM Holes Array

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Abstract

Debris distribution in the bottom and side gap significantly affects machining performance of electrical discharge machining (EDM) of holes array. Therefore, the mechanisms of debris distribution and velocity field of flow field in the discharge gap between tool electrode and work piece during EDM process should be investigated. However, these mechanisms have not been fully understood because it is difficult to observe debris distribution process. In this paper, a two-dimensional model of flow field with liquid and debris phase for the bottom and side gap in ultrasonic assisted EDM of holes array was created by computational fluid dynamics. The debris distribution and velocity field of flow field in the bottom and side gap during an ultrasonic vibration cycle was investigated through the numerical simulation. The results show that holes in the center of the array are larger than those at the periphery, which is caused by difference of debris distribution. Machining experiments were conducted to verify the simulation results of debris distribution during EDM of holes array.

Keywords: *Electrical discharge machining (EDM), Debris distribution, velocity field, Numerical simulation*

1. Introduction

The micro-holes array machining is always a hot spot and difficult problem in the field of mechanical machining. Duo to non-contact machining via the thermomechanical effect regardless of the hardness of the work piece material, electrical discharge machining (EDM) has been widely used for manufacturing micro-hole array, such as ink-jet nozzle, precision optical fiber connector and fuel spray nozzle [1]. During EDM process, conductive materials is eroded into debris by sequential electrical discharge pulses generated between tool electrodes array and work piece when both are immersed in dielectric oil. However, on account of not rotating electrodes array, the debris tends to accumulate in the bottom and side gap in the electrical discharge machining of holes array. When debris concentration reaches a specified level, accumulative debris will give rise to highly concentrated distribution of discharge point in space and time, which significantly influences EDM performance [2].

In order to improve machining stability and machining efficiency of EDM of holes array, a number of researchers attempted to work theoretically and experimentally on EDM of holes array. For example, Zeng experimentally analyzed the influence of ultrasonic vibration on the EDM of micro-holes array, and discussed diameter fluctuation of micro-holes array and machining efficiency [3-4]. Tong reported that a cyclic alternating process of micro-electrode repeated machining and micro-holes drilling was implemented for micro-holes array with high consistency accuracy by a tangential feed WEDG method [5]. Yi fabricated a metal shadow mask for organic thin-film transistors by batch mode electro-discharge machining, and improved the productivity to five times

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of that in the case of using a single tool electrode [6]. Hwang fabricate the micro-pin array made of tungsten carbide by the combination of multi-stage micro-hole electrodes array and three debris removal methods in a reverse-EDM process [7]. Wang proposes a three-dimensional model of flow field with liquid, gas, and solid phases for machining gap in EDM to investigate the mechanisms of debris and bubble movement in the machining gap during consecutive-pulse discharge, and the results showed that the bubble expansion is the main way that the bubbles exclude from machining gap [8]. In the studies reported in [9], an array of 20×20 Cu electrodes with 20 μm diameters was fabricated by LIGA and used to machine through-holes in 50 μm thick stainless steel. Variation of perforation diameter along a diagonal of the holes array is relatively large compared to the 2-3μm gap which can be achieved by rotating single electrodes under comparable operating conditions. In addition, holes in the center of the array are larger than those at the periphery. The enlargement of the hole is believed to be caused by debris distribution and concentration. Recent work has demonstrated that debris distribution and concentration significantly affects the machining performance of EDM process. Therefore, the mechanisms of debris distribution and velocity field during EDM of holes array should be elucidated.

In this paper, a two-dimensional model of flow field with liquid and debris phases for the bottom and side gap in ultrasonic assisted EDM of holes array was created by computational fluid dynamics. Debris distribution and velocity field during EDM of holes array was investigated based on the model when the tool has ultrasonic vibration. Machining experiments were conducted to verify the simulation results.

2. Mathematical Basis of the Simulation Model

The numerical simulation were carried out by computational fluid dynamics software FLUENT. The volume of fluid model was used to calculate the movement of EDM kerosene (liquid phase) and debris (solid phase) in the bottom and side gap in the process of ultrasonic assisted EDM of holes array. The debris was dealt with using discrete phase model by solving a continuity equation. Fluid flow follows the laws of energy conservation, mass conservation and momentum conservation, which is Navier-Stokes equation. Regardless of the heat transfer effect, in this study mass conservation and momentum conservation were solved throughout the flow field domain.

The Navier-Stokes equation had the following form:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_x)}{\partial x} + \frac{\partial (\rho u_y)}{\partial y} + \frac{\partial (\rho u_z)}{\partial z} = 0 \tag{1}$$

$$\frac{\partial (\rho u_x)}{\partial t} + \nabla \cdot (\rho u_x \vec{u}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \tag{2}$$

$$\frac{\partial (\rho u_y)}{\partial t} + \nabla \cdot (\rho u_y \vec{u}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \tag{3}$$

$$\frac{\partial (\rho u_z)}{\partial t} + \nabla \cdot (\rho u_z \vec{u}) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \tag{4}$$

Where u_x, u_y and u_z is velocity component in the X, Y and Z direction, respectively; t is time; ρ is the density; τ_{xx}, τ_{xy} and τ_{xz} are the component of viscous force τ on infinitesimal body surface; p is press on infinitesimal fluid unit; f_x, f_y and f_z, are mass force in the X, Y

and Z direction, respectively.

Because the debris moved with the dielectric fluid in the machining gap, their movement abided by Newton's Second Law. The motion equation of the debris in the gap flow field in the X direction at Cartesian coordinates can be described as follows:

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} + F_x \tag{5}$$

Where u and u_p are the velocities of kerosene and debris, respectively; ρ_p and ρ are the densities of kerosene and debris, respectively; g_x is the acceleration of gravity; $F_D(u\text{-}u_P)$ is the drag force of the debris. F_D is calculated as follows:

$$F_D = \frac{C_D R_e}{24} \frac{18u}{\rho_P d_P^{\ 2}} \tag{6}$$

Where C_D is the coefficient of the drag force, R_e is the Reynolds number, and d_p is the diameter of the debris.

F_x is added mass force, calculated as follows:

$$F_x = \frac{1}{2} \frac{\rho}{\rho_p} \frac{d}{dt}(u - u_p) \tag{7}$$

The vibration of the tool can be expressed as:

$$y = A\cos(2\pi\, ft + \phi) \tag{8}$$

Where y is the displacement of the tool, t is time, f is the frequency of the tool vibration, which is 20 KHz, and A is the maximum amplitude of the tool vibration, which is 4μm and ϕ is phase angle difference. The velocity of the tool vibrating is:

$$v = 2\pi Af \sin(2\pi\, ft + \phi) \tag{9}$$

3. Geometric Model of Machining Gap

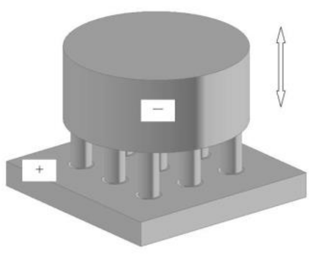


Figure 1. Schematic of Ultrasonic Assisted EDM of Holes Array

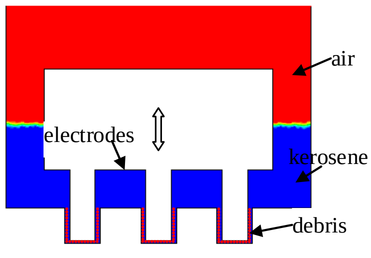
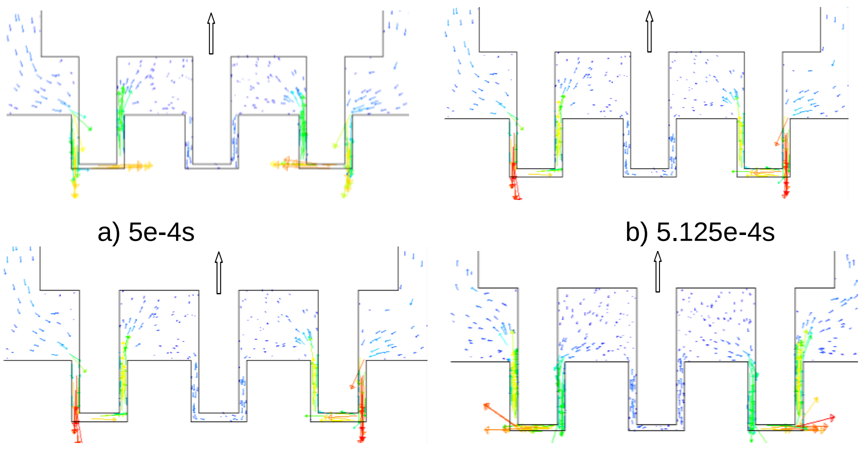


Figure 2. Geometric Model of Machining Gap

Figure 1 displays a diagrammatic sketch of ultrasonic assisted EDM of holes array. Due to using immersion processing, the lower part of the tool electrodes immerses in the liquid kerosene, while the upper part of the tool electrodes immerses in the air, the volume of fluid model has been involved in the processing of kerosene and air two-phase flow problem, the moving grid technology and the discrete phase model of FLUENT software has been conducted. Figure 2 shows the initial location of the debris. Debris is set to the same spherical of 5 micron in diameter, and that the density of the debris is equal to that of iron and uniformly distributed in the bottom and side gap in a discrete phase model.

4. Simulation Results and Discussion

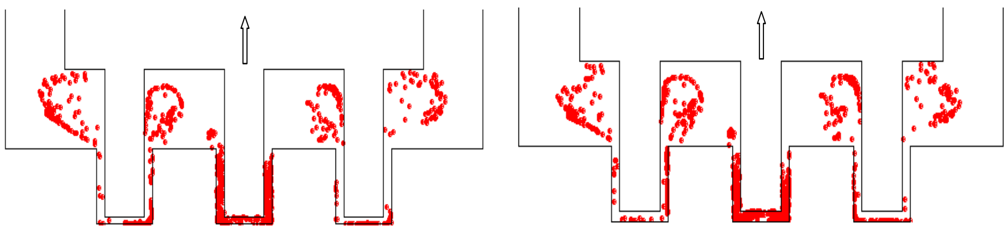
This study investigated the evolution of debris distribution and velocity field in the bottom and side gap in an ultrasonic vibration period after ten ultrasonic vibration periods. Figure 3 refers to the simulation results of velocity field of the flow field in a period of ultrasonic vibration. Figure 3(a), 3(b) shows when the electrode is jumping up, the working liquid is moving inward. Figure 3(c), 3(d) shows when the electrode is jumping down, the working liquid is moving outward. Figure 4 showed the simulation results of the debris movement. When the electrode is jumping up, the debris moved toward the bottom gap from the side gap, and the debris concentration increases at the end of the electrode jump motion. When the electrode is jumping down, the debris moved toward the side gap from the bottom gap, and the debris concentration decreases at the end of the electrode jump motion.



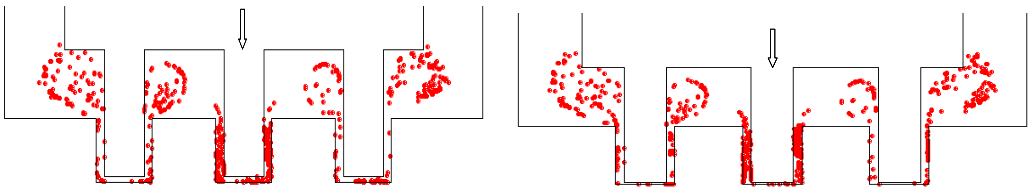
a) 5e-4s b) 5.125e-4s

c) 5.25e-4s d) 5.375e-4s

Figure 3. The Evolution of Velocity Field in an Ultrasonic Vibration Period



a) 5e-4s b) 5.125e-4s



c) 5.25e-4s d) 5.375e-4s

Figure 4. The Evolution of Debris Distribution in an Ultrasonic Vibration Period

During the ultrasonic vibration process, when the electrodes array jumped up at a speed, then pressure field beneath the electrode was lower than atmospheric pressure. Once the pressure is lower than the atmospheric pressure, the clean working liquid rapidly moves inward the gap between the tool electrodes array and work piece. Then, the debris moved toward the bottom gap from the side gap when the electrode jumped up. The debris concentration in the bottom gap increased at the end of the electrode jump motion. Whereas the electrodes array jumped down, then pressure field beneath the electrode was higher than atmospheric pressure. When the pressure is higher than the atmospheric pressure, the working liquid mixed debris rapidly moves outward the bottom gap. Then, the debris moved toward the side gap from the bottom gap when the electrode jumped down. The debris concentration in the bottom gap decreased at the end of the electrode jump motion.

Regardless of the moving direction of the debris and velocity field, the dispersion degree of debris in the outside hole is more than the middle hole, because the velocity speed of the flow field in the outside hole is more than the middle hole. The stability of electrical discharges in the working gap is directly influenced by the debris distribution, which is directly influenced by flow field of working fluid. When much debris stagnates in the bottom and side gap, the secondary discharges possibly occur on the same location, which leads to unstable machining performance and low shape accuracy.

5 Experiments

Holes array is drilled with a 3×3 tool electrodes array in the EDM machine. Tool electrodes array is 30 micron in diameter and 250 micron interval distance of 3×3 cylindrical shaped tungsten electrodes array, which has ultrasonic vibration in order to improve EDM performance. Work piece is 90 micron thick of 65Mn slice, which connects RC power supply anode. The machining conditions are shown in Table 1. SEM micrographs of tool electrodes array is shown in figure5. After drilling, SEM micrograph of micro-holes array illustrates variation of diameter of the holes array when machining is performed under comparable operating conditions (Figure 6). It is shown that holes in the center of the array are larger than those at the periphery, which is deemed to be caused by debris distribution and concentration. The work has demonstrated that debris distribution and concentration significantly affects the machining performance of EDM process.

Table 1. Machining Parameters

parameters	values
tool	3×3tungsten
workpiece	65Mn slice
Capacitance(p	4700
working	kerosene
Voltage(V)	100

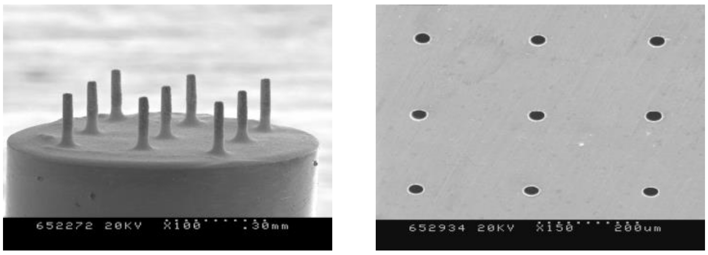


Figure 5. SEM Photographs of Tool Electrodes and Holes Array

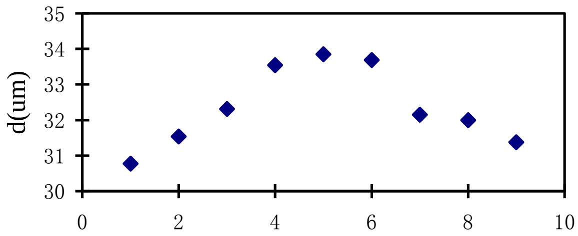


Figure 6. Diameter Fluctuation Curve f Micro-Hole Array

6. Conclusions

In this current study, debris distribution and velocity field during EDM of holes array was investigated based on the numerical simulation and experiments. The following main conclusions were drawn:

1) A two-dimensional flow field model with liquid and debris phases in ultrasonic assisted EDM of holes array was created by computational fluid dynamics. Debris distribution and velocity field during EDM of holes array was carried out based on the numerical simulation and experiments.

2) Holes in the center of the array are larger than those at the periphery, which is caused by difference of debris distribution. Difference of debris distribution significantly affects the machining performance of EDM process.

Acknowledgments

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