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Numerical Study of Debris Distribution in Ultrasonic Assisted EDM of Hole Array under Different Amplitude and Frequency

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Abstract

Debris accumulation in the bottom and side gap leads to a poor machining stability and low machining efficiency of electrical discharge machining (EDM). Thus, an understanding on the mechanisms of debris distribution and exclusion of flow field in the discharge gap during EDM process should be investigated. However, these mechanisms have not been fully understood because debris distribution and exclusion process in the bottom and side gap is difficult to simulate and observe. This paper suggests a two-dimensional model of flow field with kerosene and debris phases for the bottom and side gap in ultrasonic assisted EDM process by computational fluid dynamics. The mechanism of debris distribution and exclusion in the discharge gap during ultrasonic vibration cycle was researched through the model. The effect of amplitude and frequency of ultrasonic vibration of the tool on debris distribution and exclusion during electrical discharge machining of whole array was investigated through numerical simulation. It is shown that ultrasonic vibration of the tool has significantly influence on the debris exclusion from discharge gap. In addition, the debris distribution and exclusion becomes strong with the increase of the amplitude and frequency of ultrasonic vibration of the tool.

Keywords: *Electrical discharge machining (EDM), Ultrasonic vibration, Debris, Numerical simulation*

1. Introduction

With the development of precision and microminiaturization products, micro-hole array has been widely used in aerospace as well as automotive, and surgical components, for example, precision optical fiber connector, inkjet nozzle and fuel spray nozzle. However, micro-hole array machining has been always the hot and difficult issue in the field of mechanical machining. Nowadays, laser processing technology [1], LIGA technology [2], micro-EDM [3] and micro-ECM [4] are the main method of micro-hole array machining. Due to expensive equipment investment and harsh operating environment, the application of laser processing technology and LIGA technology are limited. However, Micro-EDM, which has low machining cost and mature technology, is non-contacting processing and no obvious macroscopic reaction and has especial process advantages in micro-hole array machining.

Duo to its not rotating electrodes array, the debris tends to accumulate in the bottom and side gap in the electrical discharge machining of whole array. When debris concentration reaches a specified level, debris accumulation will give rise to highly concentrated distribution of discharge point in space and time, which significantly influences EDM performance [5]. In order to improve machining stability and machining efficiency of EDM of hole array, a number of researchers attempted to work experimentally on the ultrasonic vibration assisted EDM of holes array. For example, Zeng *et al.* experimentally analyzed the influence of ultrasonic vibration on the EDM of

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micro-holes array, and discussed diameter fluctuation of micro-hole array and machining efficiency [6-7]. Yi *et al.* fabricated A metal shadow mask for organic thin-film transistors by batch mode electro-discharge machining, and improved the productivity to five times of that in the case using a single electrode [8].Tong *et al.* reported that a cyclic alternating process of micro-electrode repeated machining and micro holes drilling was implemented for array micro holes with high consistency accuracy by a tangential feed WEDG method [9]. Hwang *et al.* 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 [10].

In this paper, a two-dimensional model of flow field with liquid and debris phases for the bottom and side gap in the process of electrical discharge machining was found by computational fluid dynamics. The effect of ultrasonic vibration of the tool on debris distribution and exclusion during electrical discharge machining of holes array was investigated based on the model when the tool has ultrasonic vibration.

2. Mathematical Basis of the Simulation Model

The numerical simulation in this paper 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 electrical discharge machining 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 *ux*, *uy* and *uz* is velocity component in the X, Y and Z direction, respectively; *t* is time; *ρ* is the density; *τxx*, *τxy* and *τxz* are the component of viscous force *τ* on infinitesimal body surface; *p* is press on infinitesimal fluid unit; *fx*, *fy* and *fz*, 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 [11]:

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

Where *u* and *up* are the velocities of kerosene and debris, respectively; *ρp* and *ρ* are the densities of kerosene and debris, respectively; *gx* is the acceleration of gravity; *FD*(*u-uP*) is the drag force of the debris. *FD* was calculated as follows:

$$F_D = \frac{C_D R_e}{24} \frac{18u}{\rho_p d_p^2} \quad (6)$$

Where *CD* is the coefficient of the drag force, *Re* is the Reynolds number, and *dp* is the diameter of the debris.

The vibration of the tool can be expressed as:

$$y = A\cos(2\pi ft + \phi) \quad (7)$$

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

$$v = 2\pi Af \sin(2\pi ft + \phi) \quad (8)$$

3. Geometric Model of Machining Gap

Figure1 displays a diagrammatic sketch of ultrasonic assisted EDM of holes array in this study. Due to using immersion processing way in ultrasonic assisted EDM of hole array, the lower part of the electrodes array immerses in the liquid kerosene, while the upper part of the electrodes array immerses in the air, The volume of fluid model has been involved in the processing of kerosene and air two-phase flow problem. In order to directly observe the debris distribution and exclusion of flow field in ultrasonic vibration process, the moving grid technology and the discrete phase model of FLUENT software has been conducted the debris distribution and movement of flow field. Figure1 shows the initial location of the debris to be tracked. Debris is set to the same spherical of 5 micron in diameter, uniformly distributed in the bottom and side gap.

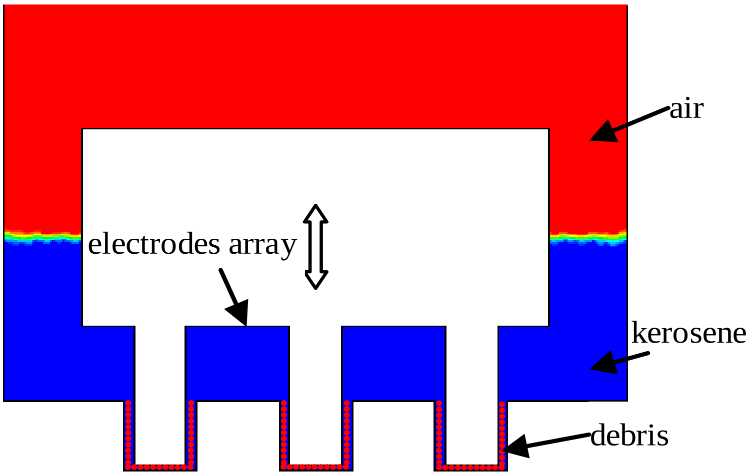


Figure 1. Schematic of Ultrasonic Assisted EDM of Hole Array

To simplify the numerical calculation, the flow field far away from the machining gap was disregarded. The sizes of the electrode array and fabricated hole array are measured; the difference between these sizes is the size of the side gap. The size of the bottom gap and the side gap are hypothetically the same. Tool is 50 micron side length and 150 micron interval distance of 3×3 square-shaped tungsten electrode array, which has ultrasonic vibration in order to improve EDM performance. Work piece is 30 micron thick 65Mn slice, which connects RC power supply anode. The machining conditions are shown in Table 1.

Table 1. Machining Parameters

parameters	values
tool	3×3 tungsten electrode array
work piece	65Mn slice
Capacitance(pF)	4700
working medium	kerosene
Voltage(V)	100

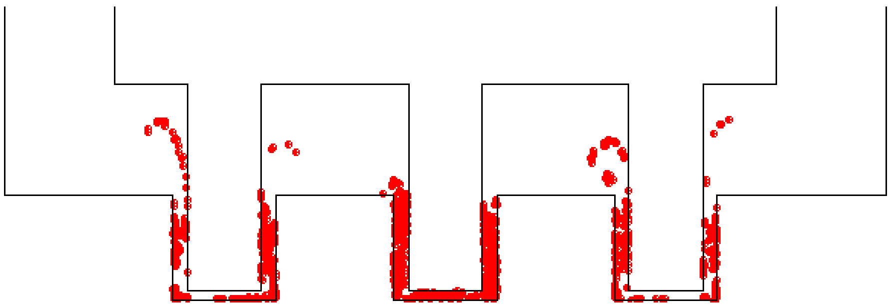
4. Results and Discussion

Cavitations, exfoliation and pump suction effect caused by High frequency ultrasonic vibration can effectively excludes the debris from discharge gap, improving the flow characteristic of the working liquid and effective pulse discharge frequency. However, the effect of amplitude and frequency of ultrasonic vibration of the tool on debris distribution and exclusion during electrical discharge machining of hole array have not been fully understood. Thus, in this section the mechanism of debris distribution and exclusion in the machining gap under different amplitude and frequency of ultrasonic vibration was studied through numerical simulation.

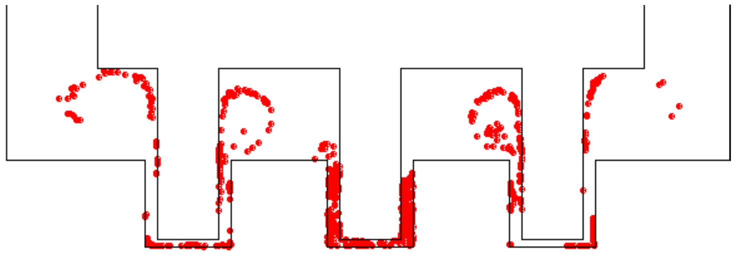
4.1. Influence of Amplitude of Ultrasonic Vibration on Debris Distribution and Exclusion

The frequency of ultrasonic vibration is set to 40 KHz and the amplitude of ultrasonic vibration changes from 1μm, 2μm and 4μm, respectively. After completing 500 microseconds ultrasonic vibration, the debris distribution and exclusion of flow field in the bottom and side gap under different amplitude of ultrasonic vibration were numerically investigated. The analyzed results of debris distribution with varying the amplitude of ultrasonic vibration from 1μm, 2μm and 4μm are shown in Figure2.

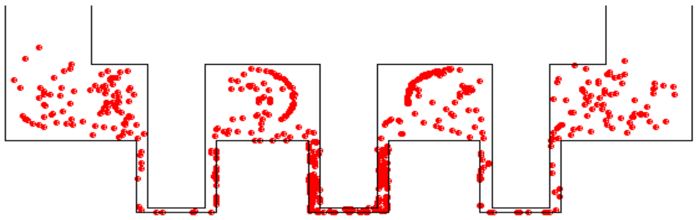
After completing 500 microseconds ultrasonic vibration under different amplitude of ultrasonic vibration conditions, debris are scattered in different degrees and excluded out from the same parts of the hole array. The amplitude of ultrasonic vibration with varying from 1μm, 2μm and 4μm greatly influence debris distribution and exclusion in the discharge gap. Under the same vibration frequency conditions, with the increase of vibration amplitude, the more the dispersion degree of debris in discharge gap and the fewer the gathered debris at the bottom of gap. The ultrasonic vibration speed of the tool increases with an increase of the amplitude of ultrasonic vibration. Effect of the cavitations, exfoliation and pump suction of ultrasonic vibration is remarkable, which can effectively exclude debris from the discharge gap.



a) 1μm



b) 2μm



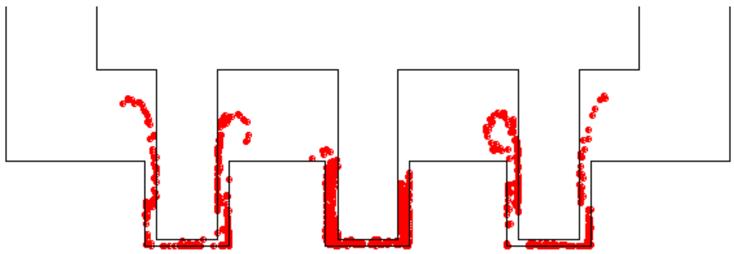
c) 4μm

Figure 2. Debris Distribution of Flow Field Under Different Amplitude of Ultrasonic Vibration After Completing 500 Microseconds Ultrasonic Vibration

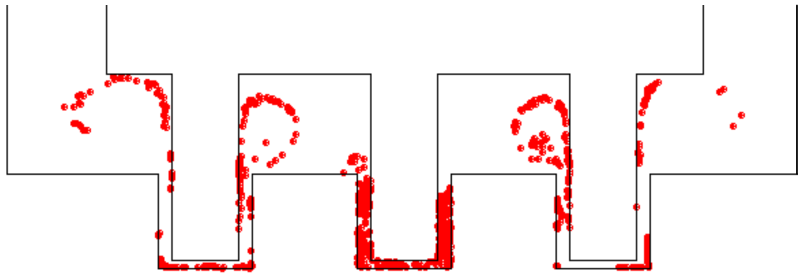
4.2. Influence of Frequency of Ultrasonic Vibration on Debris Distribution and Exclusion

The amplitude of ultrasonic vibration is set to 2μm and the frequency of ultrasonic vibration changes from 20 KHz, 40 KHz and 60 KHz, respectively. After completing 500 microseconds ultrasonic vibration, the debris distribution and exclusion of flow field in the bottom and side gap under different amplitude of ultrasonic vibration were numerically investigated. The analyzed results of debris distribution with varying the frequency of ultrasonic vibration from 20 KHz, 40 KHz and 60 KHz are shown in Figure3.

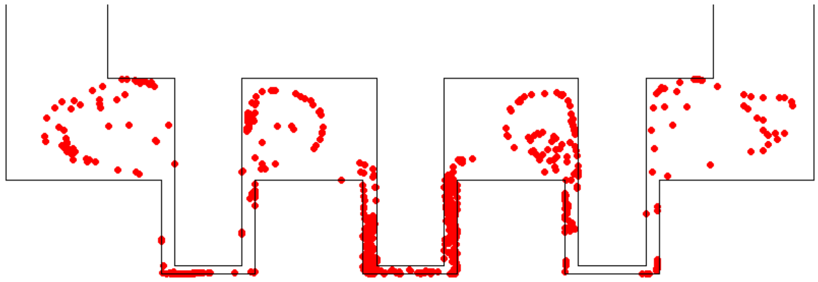
After completing 500 microseconds ultrasonic vibration under different frequency of ultrasonic vibration conditions, debris are scattered in different degrees and excluded out from the same parts of the hole array. The frequency of ultrasonic vibration with varying from 20 KHz, 40 KHz and 60 KHz greatly influence debris distribution and exclusion in the discharge gap. Under the same vibration amplitude conditions, with the increase of vibration frequency, the more the dispersion degree of debris in discharge gap and the fewer the gathered debris at the bottom of gap. This is because the ultrasonic vibration period of the tool increases with an increase of the frequency of ultrasonic vibration. Effect of the cavitations, exfoliation and pump suction of ultrasonic vibration is remarkable, which can effectively exclude debris from the discharge gap.



a) 20 KHz



b) 40 KHz



c) 60 KHz

Figure 3. Debris Distribution of Flow Field Under Different Frequency of Ultrasonic Vibration after Completing 500 Microseconds Ultrasonic Vibration

The numerical simulation results show that ultrasonic vibration of the tool has significantly influence on the debris exclusion from machining gap. In addition, the debris distribution and exclusion becomes strong with the increase of the amplitude and frequency of ultrasonic vibration of the tool. Regardless of the frequency and amplitude of ultrasonic vibration, 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.

5. Conclusions

Debris accumulation is one of the most important factor for machining stability and machining efficiency of electrical discharge machining. It is important and essential to analyze the debris distribution and exclusion of flow field in the discharge gap during EDM process. In this paper, we can conclude that:

1) A two-dimensional model of flow field with kerosene and debris phases for the discharge gap in the process of ultrasonic assisted electrical discharge machining by computational fluid dynamics. The mechanism of debris distribution and exclusion in the machining gap was investigated through the model.

2) The effect of amplitude and frequency of ultrasonic vibration of the tool on debris distribution and exclusion during electrical discharge machining of hole array was investigated. The debris distribution and exclusion becomes strong with the increase of the amplitude and frequency of ultrasonic vibration of the tool.

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