Study on Gap Flow Field Simulation in Small Hole Machining of Ultrasonic Assisted EDM

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Abstract. When machining a small hole with high aspect ratio in EDM, it is hard for the flushing liquid entering the bottom gap and the debris could hardly be removed, which results in the accumulation of debris and affects the machining efficiency and machining accuracy. The assisted ultrasonic vibration can improve the removal of debris in the gap. Based on dynamics simulation software Fluent, a 3D model of debris movement in the gap flow field of EDM small hole machining assisted with side flushing and ultrasonic vibration is established in this paper. When depth to ratio is 3, the laws of different amplitudes and frequencies on debris distribution and removal are quantitatively analysed. The research results show that periodic ultrasonic vibration can promote the movement of debris, which is beneficial to the removal of debris in the machining gap. Compared to traditional small hole machining in EDM, the debris in the machining gap is greatly reduced, which ensures the stability of machining process and improves the machining efficiency.

1. Introduction

Electrical discharge machining (EDM) as a non-traditional machining method uses the electrothermal effect of pulse discharge between two electrodes to remove materials in dielectric fluid. As there is no mechanical contact between the tool and workpiece during the whole process, it isn’t restricted to mechanical properties of the strength of material and the hardness of material, etc. thus EDM has been successfully extended to the field of small hole[1]. However, a lot of debris is generated in the small hole EDM machining process. If the debris in machining gap is not removed in time, it will be accumulated and linked between the electrode and workpiece, which easily leads to the arc discharge and short circuit, affecting machining quality and material removal rate. Flushing is a common method for promoting debris removal in EDM operation, it is a process that makes dielectric fluid get into the machining gap, which will improve fluid mobility and be beneficial to debris removal. But the research indicates that when machining the hole with high aspect ratio, the large machining depth makes flushing difficult to enter the machining gap and to remove the debris[2]. When the depth to diameter ratio of hole is large, the problem of debris removal can be solved with the help of ultrasonic vibration.

Aimed at the problem of debris removal ultrasonic assisted EDM, Y Imai et al. made researches on the effect of the high-frequency response of piezoelectric actuator on the speed of EDM and summarized that the high-frequency vibration can increase the machining speed in fine machining, high smooth surface and ϕ240μm micro-hole machining approximately 1.5-2.5 times faster than
before[3]. Garn et al. conducted experiments to analyse and concluded that ultrasonic vibration can weaken the effect of systematic delay on processing, reduce arc discharge and improve machining efficiency and surface quality[4]. SA Mastud et al. set up a simulation model of debris movement with ultrasonic vibration. The study found that the amplitude and frequency make the effect of debris movement and accelerate the debris movement[5]. T Zhu et al. researched the effect of ultrasonic vibration on the gap flow field in electrical-discharge milling and showed that the pressure field of cyclical ultrasonic frequency enhances cavitation effect, accelerates dielectric fluid circulation and improves machining stability and machining efficiency[6]. W Chang et al. studied the pressure field, velocity field and the concentration of debris particles in machining gap during a period of ultrasonic vibration with Fluent. Simulation results show that ultrasonic vibration is beneficial to the removal of machining debris from inter-electrode gap[7].

Given many available models, due to the debris movement in high aspect ratio hole EDM machining with ultrasonic vibration and side flushing is not yet fully understood. This paper developed a model to simulate the distribution and removal of debris when the depth to diameter ratio is 3 in ultrasonic assisted EDM with side flushing in fluid dynamical simulation software Fluent and analyse the influence of different parameters during the operation.

2. Establishing for the Model of Inter-Electrode Gap Field

The debris removal process in ultrasonic assisted EDM process for machining small hole is shown in figure 1 The flushing circulates the dielectric liquid in the bottom gap. Meanwhile, amplitude transformer drives the tool to do up and down reciprocating ultrasonic vibration. In this process, due to enhancement of cavitation effect, the electrode causes pressure difference and debris that are generated between two electrodes along with the working liquid is pushed to the region with lower pressure from the region with higher pressure. As the greater mobility of debris and the disturbance of tool vibration in the bottom gap, debris is removed from the bottom gap and side gap, finally removed out of small hole.

![Figure 1. Process of debris motion in small hole machining of ultrasonic assisted EDM.](image)

2.1. Mathematical Model of Inter-Electrode Gap Flow Field

Debris gains speed and moves by getting the impact from the flowing of dielectric liquid in the gap flow field. Newton's laws of motion are applied to the unit mass particles and derive differential kinetic equation[8]. The equation can be written (for the x direction in Cartesian coordinates) as

\[
\frac{dv}{dt} = F_D(\bar{v} - \bar{v}_p) + \frac{g(\rho_p - \rho)}{\rho_p} + \vec{F}
\]

where \( F_D(\bar{v} - \bar{v}_p) \) is the drag force per unit particle mass, \( \bar{v}_p \) is the particle velocity, \( \bar{v} \) is the fluid phase velocity, \( F_D \) is expressed as

\[
F_D = \frac{18\mu C_d \text{Re}}{24\rho_p d_p^2},
\]

\( \mu \) is the molecular viscosity of the fluid, \( d_p \) is
the particle diameter, $\rho$ is the fluid density and $\rho_p$ is the particle density. $\vec{F}$ is an additional acceleration term and here consider to be the ultrasonic vibration force.

$$\vec{F} = \frac{dv}{dt} = \frac{d}{dt} \left[ \frac{2\pi fA \cos(2\pi ft + \phi)}{t} \right]$$

where, $f$ is the frequency of ultrasonic vibration, $A$ is amplitude, $t$ is processing time, $v_u$ is tool velocity.

2.2. Modeling for the Inter-Electrode Gap Flow Field
The gap flow field of small hole machining process is considered as a 3D cylinder model which is established and meshed in the Gambit. The electrode and flushing are both cylinders. The machining depth is 3mm. The tool electrode diameter is 1mm. Considering the mobility of working fluid, the region above the electrode is appropriately much larger. Figure 2 is the model of the gap flow field in ultrasonic assisted EDM. In figure 2, 1 is the wall of small hole, 2 is the surface of workpiece, 3 is tool electrode, 4 is flushing and 5 is the flow region of workpiece surface. The flushing tube and working fluid need to exchange data so that an interface boundary is applied, pipe orifice is set to velocity-inlet, upper boundary is set to pressure outlet and rest boundaries are set to walls as default shown as figure 2(a). The debris is generated near the electrode and workpiece. In order to improve the accuracy and efficiency of calculation, the grid near the bottom of electrode is finely meshed and rest regions are roughly meshed, as shown in figure 2(b). According to the previous research, the width of side gap is set to 0.2mm and height of the bottom gap is set to 0.1mm. Hence, the cylindrical region (A1) is the bottom gap, circular region (A2) is the side gap and upper cylindrical region (A3) is the exterior flowing region, as shown in figure 2(c).

![Figure 2. Model of the gap flow field in EDM.](image)

This paper uses Fluent to simulate the real machining process. The dynamic mesh technique provided by Fluent is used to solve the problem that the shape of flow field is constantly changing in response to the ultrasonic vibration of the tool electrode. The smoothing and remeshing method are applied. The secondary development interface UDF module is also used to simulate the process[9]. In order to simulate the generation of debris in different positions, functions are programmed to generate random numbers. In terms of the fact that the random function on the computer is a fake random, a function sleep for delaying is called every time when generating a random number. Then ranPosition function is called to generate the positions each discharge. The debris particle materials are copper and Ti alloy respectively. Tool is red copper. Workpiece material is TC4. As the bottom of the electrode is applied with velocity-inlet, laminar-model is used to establish and simulate the flow field.

3. Simulation Results and Analysis
The process of different amplitudes and frequencies within 0.04s is simulated and the debris movement and the velocity of gap flow field are analysed. Pressure solver is set in Fluent. The time is transient. Working fluid is deionized water. The velocity of flushing is 2 m/s. The macro function
DEFINE_CG_MOTION is written and compiled to implement the ultrasonic vibration of electrode. Simulation time is 0.00001 and time step is 4000. The simulation results are shown as follows.

3.1. Impact of side flushing on the removal of debris

Figure 3 and figure 4 are the simulation results without ultrasonic vibration at 0.04s. Figure 3 is debris distribution and figure 4 is velocity field.

![Figure 3](image1.png)  ![Figure 4](image2.png)

Figure 3. The debris distribution.  Figure 4. The velocity field.

It is shown in figure 3 that the abundant debris are gathered at the lower right corner and cannot be removed from the machining gap when there is only the effect of side flushing without electrode ultrasonic vibration. Because of the large depth of hole, the machining gap becomes narrow and flowing resistance is increased. It is hard for the flushing liquid overcomes the resistance to enter the side gap and to arrive at the bottom gap and it has a weak effect for the debris movement, which results in the accumulation of debris and could generate the arc discharge and short circuit. It is shown in figure 4 that the velocity of fluid in the bottom gap is approximately 0m/s. The flushing has little effect on the removal of debris.

3.2. Impact of vibration amplitude on the removal of debris

It is shown that the debris distribution with ultrasonic vibration frequency of 20kHz at 0.04s in figure 5 and the (a), (b) and (c) are respectively the debris distribution in the case of the amplitude of as 5µm, 10µm and 20µm.

![Figure 5](image3.png)

(a) Amplitude of 5µm  (b) Amplitude of 10µm  (c) Amplitude of 20µm

Figure 5. The debris distribution of the gap flow field.

Compared with the simulation result without ultrasonic vibration as shown in figure 3, the debris movement with ultrasonic vibration is more active, and most of debris in the bottom gap moves into the side gap and even is removed out of the machining gap. The accumulation of debris at bottom is obviously reduced. This is due to the fact that the electrode under the assistance of ultrasonic vibration does the up-and-down piston motion. When the electrode moves up, a negative pressure region is generated in the bottom gap of electrode and the pressure gradient of the entire gap flow field is greater. When the electrode moves down, the working fluid is squeezed by the lower surface of electrode and it is moved from the bottom gap to the side gap and even expelled. This process drives the debris to be removed from the machining gap. figure 6 presents the velocity field with different amplitudes in the gap flow field. It is found that ultrasonic vibration enlarges the effect of working
fluid disturbance in the bottom gap and the mobility of fluid is increased. Increasing flow velocity can improve the carrying capacity of working fluid to debris and promote debris at the bottom gap to be removed from the small hole.

![Velocity field of the gap flow field](image)

**Figure 6.** The velocity field of the gap flow field.

3.3. Impact of vibration frequency on the removal of debris

Figure 7 and figure 8 present the debris distribution with amplitude of 5 and frequencies of 30kHz, 40kHz respectively at the simulation time of 0.04s.

![Debris distribution](image)

**Figure 7.** The debris distribution with 30kHz. **Figure 8.** The debris distribution with 40kHz

Compared with debris distribution in figure 5(a), it is found that debris movement become more disorder and violent when increasing frequency and most of debris moves from the bottom gap to the side gap. The velocity of working fluid at the bottom gap is increased and fluid mobility is better. The accumulation of debris is reduced. As the frequency is higher, the number of longitudinal movement of electrode is also increased and the disturbance of working fluid is more violent in the vertical direction. Debris along with the working fluid, are flowed out of the bottom gap. It is beneficial to the excluding of debris.

4. Statistics and Analysis of Debris Distribution

In different amplitudes and frequencies, it is respectively counted that the quantity of debris in A1 region (bottom gap), A2 region (side gap) and A3 region (exterior flowing region) to analyse the results and to find out the relevant laws.

4.1. Impact of vibration amplitude on the debris distribution

When processing 3mm deep hole and frequency with 20kHz, figure 9 presents the quantity variation of debris with the vibration amplitudes of 5µm, 10µm and 20µm respectively in A3 region. It is shown that the quantity of debris is gradually increased in A3 region as the process progresses. By observing the velocity of debris removal (slope) with the three kinds of amplitudes, it is found that all of the velocity increases first and then incline to stable value. In addition, as the amplitude increases, the velocity of debris removed is remarkably faster. In unit time, the quantity of debris removed into A3 region is also remarkably increased.
Figure 9. The quantity variation of debris.

Figure 10. The quantity of debris distribution.

Figure 11. The quantity variation of debris.

Figure 12. The quantity of debris distribution.

4.2. Impact of vibration frequency on the debris distribution
When ultrasonic vibration amplitude is 5µm, figure 11 respectively presents the quantity variation of debris with the frequencies of 20kHz, 30kHz and 40kHz in A3 region. From figure 11, it is observed that the quantity of debris in A3 region continuously grows from 0s to 0.04s. By observing the velocities of debris removal of three frequencies, the velocities increase first and then inclines to stable value. In addition, as the frequency increases, the velocity of debris removal is remarkably faster. When the frequency increases to 40kHz, the velocity and quantity of debris removal is significantly higher than the other two cases.
removal rate increases to 4.37% when it is 30kHz. When it is 40kHz, the removal rate that is 27.9% which is much greater than the former cases. On the contrary, the higher frequency reduces residual rate of debris and they are respectively 90.45%, 65.77%, 41.07%. So it can be seen that higher frequency increases the removal rate increase and reduces the residual rate of debris. Most of debris is removed to the exterior flowing region avoiding the accumulation of debris. The results also indicate that the increasing vibration frequency has a significant effect on the removal of debris.

5. Conclusions
This paper applies the Fluent software to simulate the process of the distribution and movement of debris in small hole machining with ultrasonic assisted EDM. The laws of different amplitudes and frequencies on debris removal, the debris distribution in each region and the flow velocity distribution in the bottom gap are quantitatively researched. Through the analysis, it is found that tool electrode assisted with ultrasonic vibration promotes inter-electrode working fluid to cycle, which is beneficial to the removal of debris in the process. Moreover, as the frequency and amplitude increase, the electrode of disturbance is more violent in the bottom gap, the flow rate of working fluid flowing through the machining gap is faster, and the debris along with the working fluid is more likely to be removed from the machining gap. In addition, the low ultrasonic vibration machining parameters are weak to accelerate the removal of debris. Increasing the vibration parameters obviously improves the removal of debris in machining gap, thus ensures the processing stability and improves the process efficiency.

Acknowledgments
The financial support from the National Natural Science Foundation of China under grant number 51405058, Scientific Research Platform Foundation of Liaoning Province under grant number JDL2016006 and Talent Special Foundation of Dalian City under grant number 2016RQ054 are acknowledged.

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