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Influences of Tool Shape on the Machining Performance in EDM of Small Hole

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Abstract

Debris particles accumulation in the bottom and side clearance significantly affects the machining performance of electrical discharge machining (EDM) of small hole, especially in machining of deep-small hole. In order to improve the machining performance, the chamfered edge electrode is always an alternative as tool electrode in EDM of small hole, but few have been understood about its mechanism on the machining performance. Therefore, the flow field models of EDM of small hole with chamfered edge electrode and cylinder electrode were established using FLUENT software. Influences of tool shape on machining performance during rotary electrical discharge machining process were investigated through the numerical simulation. As a result, it was indicated that the velocity field of flow field in vertical direction in EDM of small hole is higher with chamfered edge electrode as tool electrode than cylinder electrode. The comparison experiments of EDM of small hole with chamfered edge electrode and cylinder electrode were carried out to verify the correctness of the numerical simulation.

Keywords: *Electrical discharge machining (EDM), tool shape, velocity field, Numerical simulation*

1. Introduction

With the rapid development and application of micro-manufacturing technology, small hole has been widely used in MEMS, such as fuel spray nozzle, precision optical fiber connector and spinneret plate. Duo to non-contact machining via the thermomechanical effect regardless of the hardness of the workpiece material, electrical discharge machining (EDM) has been always adopted to be an effective method to machining small hole down to 10 μm with aspect ratio of 20 [1]. However, EDM of small hole has machining problems, such as the small hole with dozens of micrometers in diameter and high aspect-ratio. But as the machining depth grows, debris particles accumulate in the bottom and side clearance, flock together to form a hill and play an active part as a tool electrode, significantly affecting machining performance of EDM of small hole using the cylinder electrode as tool electrode [2]. In order to improve the machining performance, the chamfered edge electrode is always an alternative as tool electrode in EDM of small hole to improve the debris particles' excluding efficiency, but few have been understood about its mechanism on the machining performance.

In order to improve machining performance of EDM of hole, many researchers made an attempt on EDM of hole. For example, Ekmekci *et. al.*, [3] found the tip shape changed to an inverted concaved shape in EDM of a blind micro-hole under specific machining

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conditions and machining depths, and observed the main reason is that debris particle accumulated at the tip, formed a hill and functioned as a tool electrode. The results reveal that debris particles have dominant role in EDM of micro-holes and the phenomena are illuminated experimentally with the affecting parameters to explain the wear mechanism. Yu *et. al.,* [4] have presented an effective self-flushing by applying the planetary movement of the electrode to avoid debris concentration in the narrow discharge gap causing abnormal discharges and enhance the micro-hole aspect ratio up to 18. Zhao *et. al.,* [5] have produced micro-hole with a diameter of 0.2 mm and aspect ratio of 15 in ultrasonic vibrations assisted micro-EDM. Bamberg *et. al.,* [6] actuated the EDM electrode on an orbital trajectory to drill the hole, which increases the hole diameter proportional to the orbital radius and creates a larger gap between the work piece and the electrode. The novel machining technique for micro-EDM increased the flushing to reduce electrode wear, created a better surface finish, and eliminated the exponential reduction in material removal rates typical for EDM drilling of holes with large depth to diameter ratios. Mohan *et. al.,* [7] shown that EDM drilling of aluminum silicon composite is more affected with the tube tools than solid tools. Wang and Yan [8] founded that the forced flushing yields significantly higher material removal rates for rotating electrodes with injection flushing through the center of electrode compared to the side flushing of non-rotating and rotating electrodes. Wang *et. al.,* [9] 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. Tong *et. al.,* [10] 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. Recent work has demonstrated that tool shape and electrode motion significantly affects the machining performance of EDM process. Therefore, the mechanisms of tool shape and electrode motion on velocity field during EDM of holes should be elucidated.

The influence of tool shape on machining performance of EDM of small hole is closely related to the clearance flow field during EDM during EDM process, but it is difficult to directly observe the phenomenon of clearance flow field because of opaque workpiece material. In order to understand about the mechanism of EDM machining using chamfered edge electrode, the flow field models of EDM of small hole with chamfered edge electrode and cylinder electrode as tool electrode were established using FLUENT software. Influences of tool shape on machining performance were investigated through the numerical simulation. The comparison experiments of machining of small hole were carried out to verify the numerical simulation results.

2. The Flow Field Model of EDM of Small Hole

2.1. Mathematical Basis of the Simulation Model

The numerical simulation of clearance flow field was carried out by FLUENT software. Fluid flow in EDM process abides by the laws of energy conservation, mass conservation and momentum conservation, namely the Navier-Stokes equation. In order to simply the numerical simulation process, the assumptions for dielectric fluid should be proposed. Firstly, dielectric fluid is incompressible continuous medium; secondly, the flow field physical quantity only is related to the Euler coordinate space and has nothing to do with the time. By the above hypothesis, the Navier-Stokes equation is defined as follows:

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

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

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

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

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.

2.2. Geometric Model of EDM of Small Hole

Figure 1, displays the schematic diagram of EDM of small hole with chamfered edge electrode and cylinder electrode as tool electrode. Chamfered edge electrode and cylinder electrode are immersed in dielectric fluid kerosene during rotary electrical discharge machining process. In order to simply the simulative geometric model of EDM of small hole, tool electrode and small hole is supposed as the shape of cylinder, without considering the bell shape caused by the secondary discharge phenomenon.

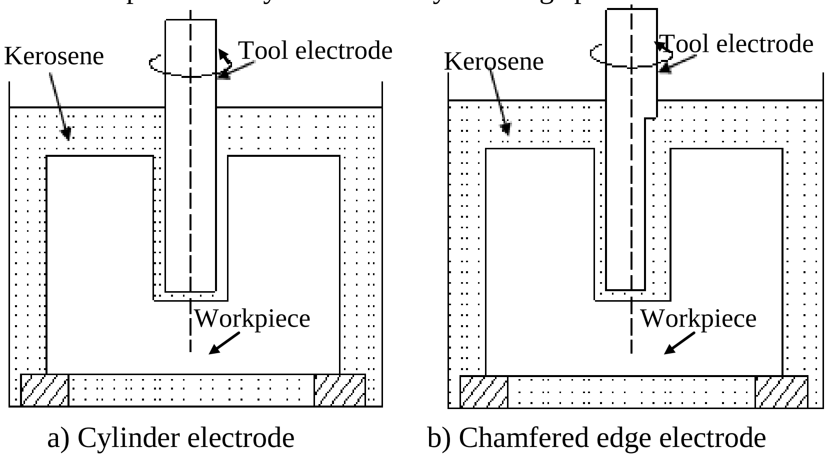


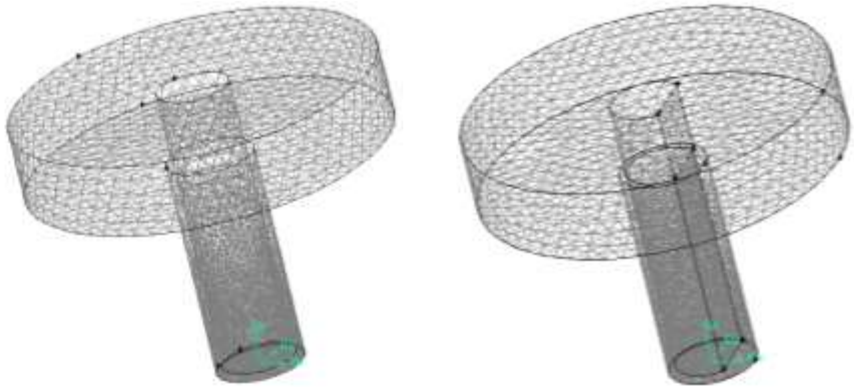
Figure 1. Schematic Diagram of EDM of Small Hole

The three dimensional clearance flow field mesh models of EDM of small hole with the chamfered edge electrode and cylinder electrode as tool electrode were found using CFD preprocess software Gambit, as is shown in Figure 2. The mesh models of EDM of small hole with the chamfered edge electrode and cylinder electrode are inside the range of rotational motions model, so the moving reference frame (MRF) model and moving grid technology in FLUENT software are used to calculate the velocity field of the clearance flow field of the chamfered edge electrode and cylinder electrode during rotary electrical discharge machining process.

The bottom and side clearance have play an important role in machining stability during EDM of small hole, but the size of the bottom and side clearance is difficult to observe and measure because of the opaque work piece material. Therefore, the size of the bottom and side clearance is estimated by the empirical equation in the simulation model. The empirical equation is defined as follows:

$$\delta_0 = K_V \cdot V + K_R \cdot \varepsilon_0^{0.4} + A_m \quad (5)$$

Where $\delta_0$is the size of the bottom and side clearance, ε_0 is discharge energy, K_R is the material factor, A_m is the mechanical shock clearance. Bringing the machining parameters into the empirical equation, the size of the bottom and side clearance is 18.2μm.



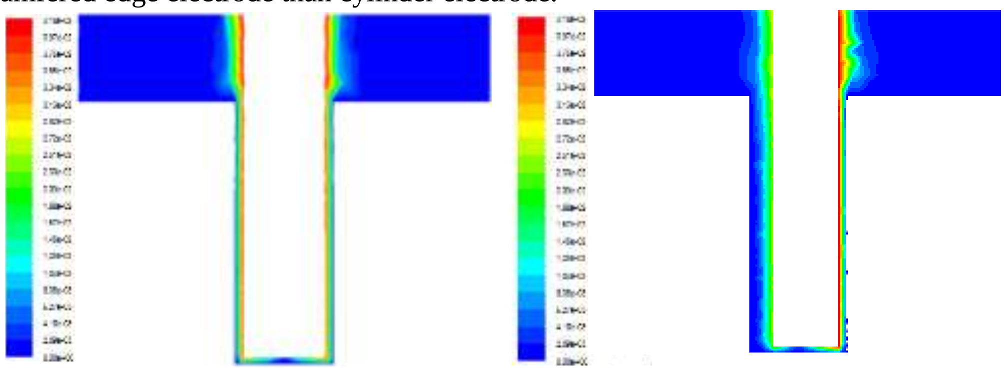
a) Cylinder electrode mesh model   b) Chamfered edge electrode mesh model

Figure 2. Simulation Model of Clearance Flow Field

The whole clearance flow field region is divided into moving regions near the rotating electrode and stationary regions away from the rotating electrode, and the interface is set in junction between moving regions and stationary regions in order to transfer data in numerical calculation. The tool electrode and moving regions near the rotating electrode rotate together at a speed of 4000r/min.

2.3. Flow Field Simulation Results and Discussion

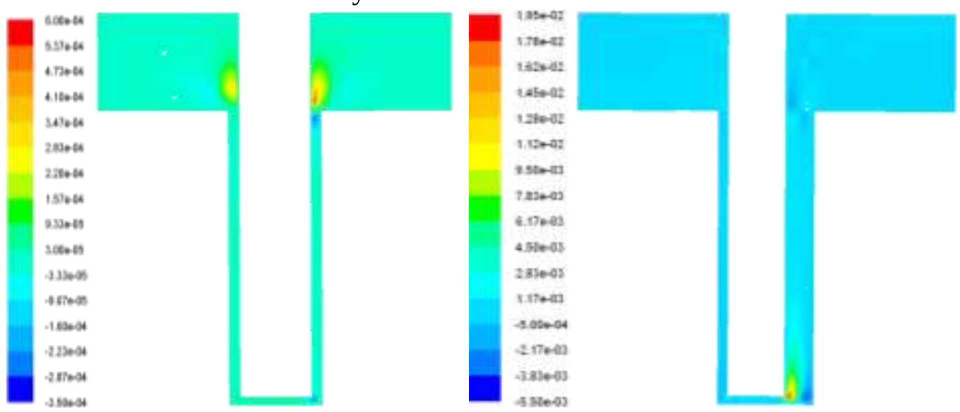
Velocity field contour of clearance flow field of EDM of small hole with cylinder electrode and chamfered edge electrode are shown in Figure 3. As shown in Figure 3, the maximum velocity value of clearance flow field of EDM of small hole is the same at the tool electrode surface location and the value of velocity field is consistent with theoretical result. Velocity field of clearance flow field are different in that the value of velocity field gradually diminishes to away from the tool electrode surface during rotary electrical discharge machining process with cylinder electrode, while the value of velocity field of the chamfered edge electrode diminishes smaller than that of cylinder electrode. It is indicated that the average velocity field of flow field of EDM of small hole is higher with chamfered edge electrode than cylinder electrode.



a) Cylinder electrode   b) Chamfered edge electrode

Figure 3. Velocity Field Contour of Clearance Flow Field

Comparing to cylinder electrode, the chamfered edge electrode is always an alternative as tool electrode in EDM of small hole to improve the machining efficiency, but few have been understood about its mechanism on debris particles' excluding process. According to EDM experience, the velocity field in vertical direction plays an important role in debris particles' excluding process. Therefore, it is necessary to analyze the influences of tool shape on the velocity field in vertical direction in EDM of small hole. The velocity field in vertical direction in EDM of small hole with the chamfered edge electrode and cylinder electrode were carried out. The velocity field contour of clearance flow field in vertical direction during rotary EDM process with cylinder electrode and chamfered edge electrode is shown in Figure 4. As is shown in Figure 4, the maximum velocity value of clearance flow field in vertical direction during rotary EDM process with cylinder electrode is 0.6mm/s at the exit, while the maximum velocity value of clearance flow field in vertical direction during rotary EDM process with chamfered edge electrode is 19.5mm/s at the bottom clearance. It can be seen that the maximum velocity value of clearance flow field in vertical direction during rotary EDM process with chamfered edge electrode is 32.5 times than with cylinder electrode.



a) Cylinder electrode b) Chamfered edge electrode

Figure 4. Velocity Field Contour of Clearance Flow Field in Vertical Direction

As is shown in Figure 4, it is all because the chamfered edge electrode as tool electrode in EDM of small hole generates more clearance for debris particles in the side clearance, reducing the debris particles concentration. The tool shape variation leads to velocity component in vertical direction during rotary EDM of small hole with chamfered edge electrode. The velocity component in vertical direction plays a very magnificent role in debris particles' excluding process. It is all because debris particles exclude from the bottom and side clearance along with the dielectric fluid under the effect of velocity component of clearance flow field in vertical direction. Comparing to the EDM of small hole with cylinder electrode, the flat micro-channel created by chamfered tool shape is always connecting with the outside dielectric fluid during EDM of small hole with chamfered edge electrode, which is in favor of excluding the debris particles and improving the machining stability. Therefore, the machining performance of EDM of small hole is more effective with chamfered edge electrode than cylinder electrode.

3. EDM Experiments

The comparing experiments EDM of small hole with the chamfered edge electrode and cylinder electrode as tool electrode are performed in EDM machine. Tool electrode is tungsten electrode with a diameter of 100μm and workpiece is 65Mn steel slice with a thickness of 10 mm, which are contacted with the RC powder. Machining parameters are shown in Table 1.

Table 1. Machining Parameters

parameters	values
tool electrode	tungsten electrode
workpiece	65Mn steel
capacitance(pF)	4700
dielectric fluid	kerosene
rotate speed(rpm)	4000
voltage(V)	150

According to the machining depth-diameter ratio, the machining time and corresponding machining depth data, the machining speed and the depth-diameter ratio data were analyzed using the fitting function $v = ye^{t}$. The fitting function is matched as follows:

$$v_c = 3.42e^{-1.5k_c} \tag{6}$$

$$v_f = 3.97e^{-0.85k_f} \tag{7}$$

Where v_c is the machining speed of cylinder electrode (mm/min); v_f is the machining speed of chamfered edge electrode (mm/min); k_c is the depth-diameter ratio of cylinder electrode; k_f is the depth-diameter ratio of chamfered edge electrode.

As is shown in Figure 5, the fitting curve of depth-diameter ratio and machining speed during EDM of small hole with chamfered edge electrode and cylinder electrode were drawn. It can be seen that the machining speed and machining efficiency is higher in short-hole than in deep-hole. The machining speed between chamfered edge electrode and cylinder electrode in initial machining time didn't appear to be much different. While the different machining speeds between chamfered edge electrode and cylinder electrode gradually present with the increasing of machining depth. It is all because the tool shape variation hasn't played the significant role in debris particles' excluding process in initial machining time. Debris particles' excluding process is fairly good. But with the increasing of machining depth, debris particles' excluding process begins to deteriorate during EDM of small hole with cylinder electrode, debris particles are unable to effectively exclude to the outside of small hole. While debris particles can be excluded from the bottom and side clearance along with the dielectric fluid under the effect of velocity component of clearance flow field in vertical direction during EDM of small hole with chamfered edge electrode. Under the influence of velocity component of clearance flow field in vertical direction, debris particles' excluding efficiency is higher in chamfered edge electrode than in cylinder electrode. Therefore, the machining depth is deeper in chamfered edge electrode than in cylinder electrode.

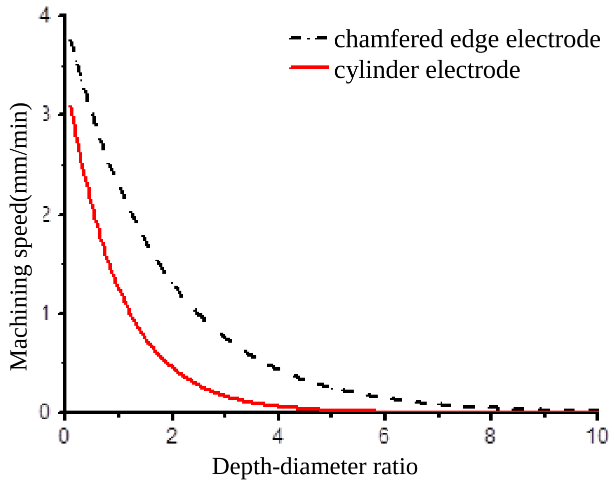


Figure 5. Curve of Depth-Diameter Ratio and Machining Speed

4. Conclusions

In this current study, influences of tool shape on machining efficiency during rotary electrical discharge machining process were investigated through the numerical simulation and experiments. The following main conclusions were drawn:

1) A clearance flow field model of EDM of small hole with chamfered edge electrode and cylinder electrode were created by computational fluid dynamics. Velocity field of clearance flow field during EDM of holes was carried out and the comparison machining experiments of small hole were carried out to verify the correctness of the numerical simulation

2) Comparing to EDM of small hole with cylinder electrode, EDM of small hole with chamfered edge electrode can effectively improve the machining depth and efficiency, it is all because velocity component in vertical direction plays a very magnificent role in debris particles' excluding process during EDM of small hole with chamfered edge electrode.

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