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Effect of Power Signal Waveform on Shape Accuracy in Elect -rochemical Drilling

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Abstract: This paper studied the effect of power signal on form accuracy in electrochemical drilling. The mathematical and physical models are built by the commercial software COMSOL. The DC signal, sine limit, triangular signal and pulse signal are selected as the research objects, and the current density of each model is simulated. The simulation results show that the average current density ranges from large to small in order of DC signal, sinusoidal signal, triangular signal and pulse signal on the anode surface. In order to verify the correctness of the model, an experiment is carried out. The experiment results show that the effect of power signal on processing size ranges from large to small in order of DC signal, sinusoidal signal, triangular signal and pulse signal. The experimental results have a good correspondence with the simulation results. We can conclude that the machining accuracy of sinusoidal and trigonometric signals is lower than pulse signals, but their processing efficiency is higher than that of pulse signals and their machining accuracy is also higher than DC signal processing accuracy. It is suitable for workpiece with high machining efficiency and moderate machining accuracy.

1. Introduction

ECM (Electrochemical Machining) is a technology of dissolving energized metal by electrochemical reaction in electrolyte solution. During the machining process, tools will not be worn out since they are not directly contacted with the workpiece. In addition, the surface quality of the machined workpiece can be very high. Therefore, this technology has been widely used manufacturing parts in fields of aeronautics & astronautics, mold and instruments & apparatus, etc[1–4]. At present, the machining accuracy of the technology is still not high enough, which limits its application in manufacturing parts of ultra high precision[5]

The power of ECM supplies the energy to drive the electrochemical reaction in the electrolytic tank[6,7]. Among ECM power sources, the one that can generate rectangular pulse waves has been most widely studied by far. Hung et al.[8] from America carried out a study of half-bridge eliminator power to generate rectangular pulse signals and applied it for ECM. It showed that the machining accuracy of the pulse power is higher than that of the DC power. Chen Wei et al.[6] found in their study that the reason why the pulse power improved the machining accuracy during the ECM process is that the average voltage of the pulse power is relatively low. With consideration of the characteristics of micro

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ECM, Spiese et al.[9] applied and experimented the rectangular pulse power for micro ECM. However, only a few people have applied different voltage signals in their experiments.

In this work, the effects of four powers (than generate DC, sinusoidal, triangular and rectangular pulse signals, respectively) on electrochemical drilling accuracy will be studied. By building both mathematical and physical models, the electric current densities generated by the four voltage signals during the machining process are simulated using COMSOL, a software than can make simulation of multi-physics fields. To verify the simulation results, the four voltage signals are also used to make the electrochemical drilling experiment. The experimental results agree well with the simulation results, which, therefore, confirms the correctness of the simulation.

2. Models

2.1Physical model

The simulation model is built on the basis of actual laboratory equipment in hand, as shown in fig. 1. In the model, the anode is made of a square sheet of 304 stainless steel（304SS）; the tool electrode is a cylindrical copper rod; and the electrolyte is 0.1mol/L ferric chloride solution.

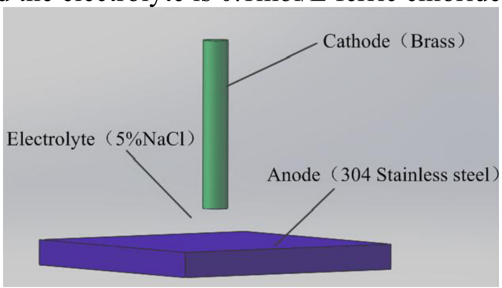


Fig.1. Physical model

2.2 Mathematical model

The value of the electric current density is jointly affected by electric field, flow field and mass transfer. For this reason, the mathematical model that takes multi-physics fields into accounts is used to study the electric current densities generated by the different voltage signals during the ECM process.

The electric field model is expressed as:

$$\nabla \cdot J = Q_j \qquad (1)$$

$$J = \sigma E + J_e \qquad (2)$$

$$E = -\nabla v \qquad (3)$$

where, J is electric current density (A/m^2); E is electric field intensity (V/m); v is electric potential (V); J_e is external electric current density (A/m^2); Q_j is current source (A/m^3); and σ is electrical conductivity (S/m).

Although the machining process is conducted in a hydrostatic environment, the rotation of the tool electrode can still generate local disturbances in the electrolyte, which accelerates the electrochemical reaction. In this case, the mathematical model of the flow field is written as:

$$\rho(u \cdot \nabla) = \nabla \cdot \left[-p\mathrm{I} + (\mu + \mu_T)\left(\nabla u + (\nabla u)^T\right)\right] + F \qquad (4)$$

$$\rho \nabla \cdot (u) = 0 \qquad (5)$$

$$\rho(u\cdot\nabla)k=\nabla\cdot\left[\left(\mu+\frac{\mu_T}{\sigma_k}\right)\nabla k\right]+\mathrm{P}_k-\rho\varepsilon \quad (6)$$

$$\rho(u\cdot\nabla)\varepsilon=\nabla\cdot\left[\left(\mu+\frac{\mu_T}{\sigma_k}\right)\nabla\varepsilon\right]+C_{e1}\frac{\varepsilon}{k}-C_{e2}\rho\frac{\varepsilon^2}{k}, \quad \varepsilon=ep \quad (7)$$

$$\mu_T=\rho C_\mu\frac{k^2}{\varepsilon} \quad (8)$$

$$P_k=\mu_T\left[\nabla u:\left(\nabla u+(\nabla u)^T\right)\right] \quad (9)$$

where, ρ is density (kg/m^3); μ is viscosity ($\mathrm{P}a\cdot s$); ε is turbulent dissipation rate; k is turbulent kinetic energy; C_{e1} and C_{e2} are two empirical constants; and P_k represents the generation of the turbulent energy caused by the mean velocity gradient.

Charged particles in the electrolyte can spontaneously generate diffusion, electromigration and convective mass transfer. The movement model is therefore expressed by the Nernst equation:

$$N_i=-D_i\nabla c_i-z_iu_iFc_i\nabla\phi_i+c_iV \quad (10)$$

wherein, N_i is the ion discharge, D_i the diffusion coefficient, c_i the electrolyte concentration, z_i the ion charge, μ_i the ion mobility, F the Faraday constant, ϕ_i the potential of the electrolyte, and V the velocity field.

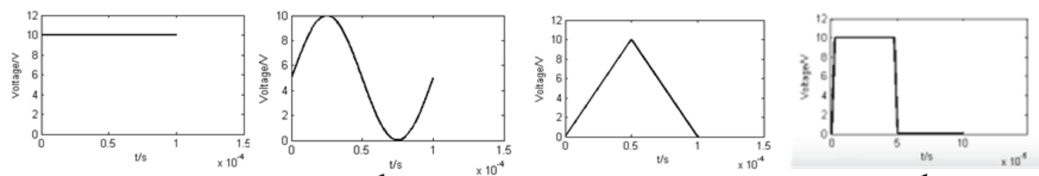
3. Simulation

3.1 Simulation parameters

During the entire simulation, the cathode is made of a copper rod with the diameter of 1mm; the anode is made of a 25x25x0.3mm square sheet of stainless steel 304; the electrolyte is 0.1mol/L $FeCl_3$ solution, and the electrode rotates at the rate of 6000r/min. See table 1 for other simulation parameters. Voltage signals with four waveforms: DC, rectangular pulse, triangular pulse and sinusoidal, are applied for the study, as shown in Fig. 2.

Table 1. Simulation parameters

Parameter	Value
anode	25×25×0.3mm 304SS
cathode	Φ1mm H62 Brass
electrolyte	$FeCl_3$
machining gap	0.12mm
cathode speed	6000r/min
voltage	10V
frequency	1000HZ



a b c d

Fig.2. Signal parameter diagram(a. DC; b. rectangular pulse; c. triangular pulse ;d. sinusoidal)

3.2 Simulation strategy
Fig. 3 shows the procedure of the simulation strategy.

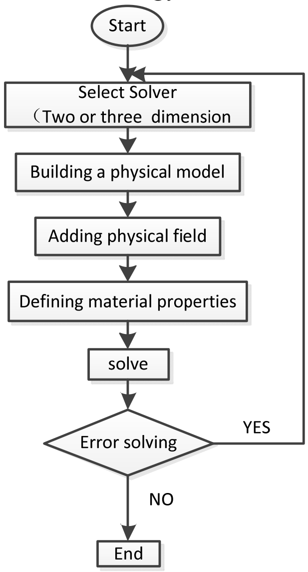


Fig.3. Simulation strategy

3.3 Simulation results
As can be known from Fig. 4-7, the electric current density corresponding to the DC signal is the largest and keeps basically unchanged during the entire period and its mean value is 5.15x10^{4}A/m^2; the electric current density corresponding to the sinusoidal signal increases at first, then decreases and increases again, and its mean value is 3.35x10^{4}A/m^2; the electric current density corresponding to the triangular signal increases from zero to the maximum, then decreases to zero again, and its mean value is 2.0310^{4}A/m^2; the electric current density corresponding to the rectangular signal increases gradually from zero, then keeps basically unchanged and decreases to zero again, and its mean value is 1.04x10^{4}A/m^2.

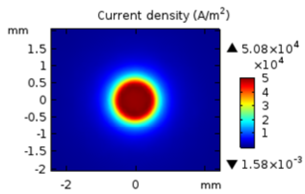


Fig.4. Simulation results of current density of DC signal

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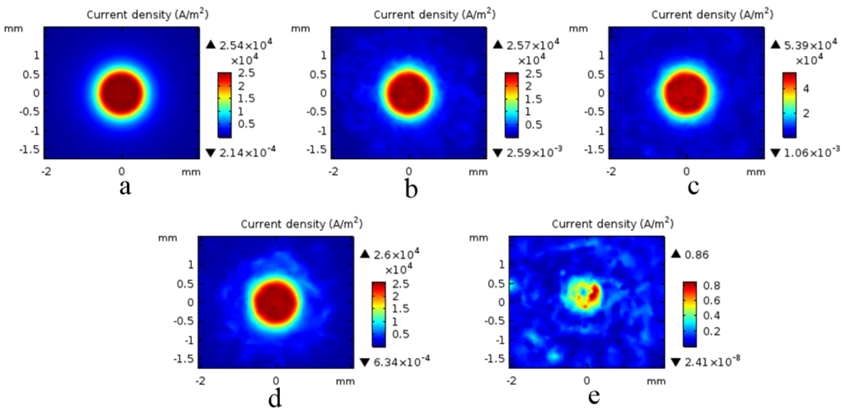

Fig.5.The simulation results of the current density of a sinusoidal signal（a. t=0s; b. $t=2.5\times 10^{-5}s$; c. $t=5.0\times 10^{-5}s$; d. $t=7.5\times 10^{-5}s$; e. $t=1\times 10^{-4}s$）

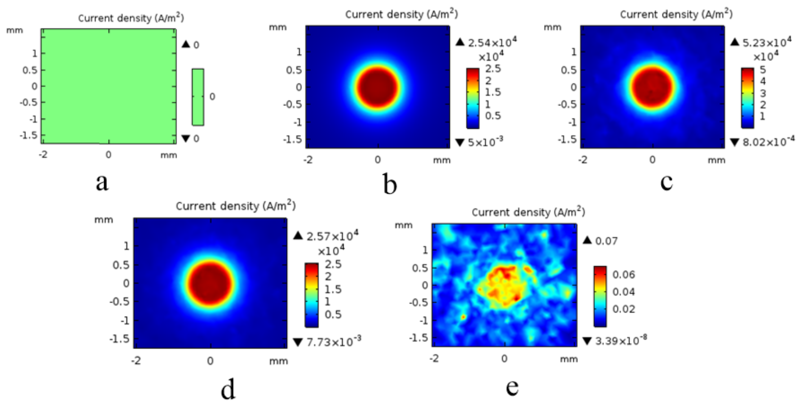

Fig.6.The simulation results of the current density of a triangular signal（a. t=0s; b. $t=2.5\times 10^{-5}s$; c. $t=5.0\times 10^{-5}s$; d. $t=7.5\times 10^{-5}s$; e. $t=1\times 10^{-4}s$）

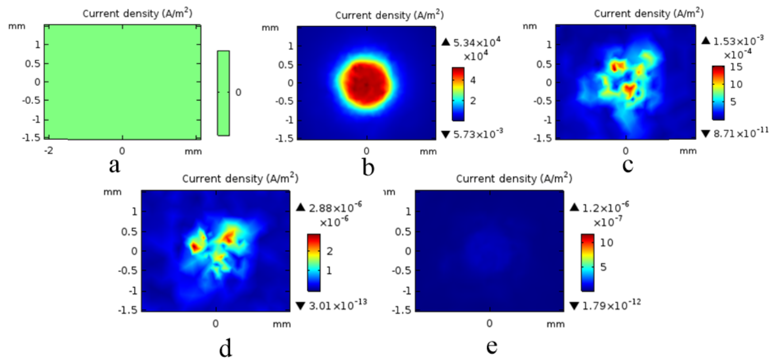

Fig.7.The simulation results of the current density of the pulse signal（a. t=0s; b. $t=2.5\times 10^{-5}s$; c. $t=5.0\times 10^{-5}s$; d. $t=7.5\times 10^{-5}s$; e. $t=1\times 10^{-4}s$）

4. Experiment

4.1 Experiment method

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The electrochemical drilling experiment is carried out for the purpose of verifying the simulation results. Figure 8 shows the experiment equipment. The machining parameters in the experiment are listed in table 2. Steps of the experiment are:

a) Remove the protective film on the surface of the stainless steel 304 and clean it using a ultrasonic cleaner.

b) Clamp the workpiece on the jig of the electrolytic tank. Set the tool and adjust the machining gap to 0.12mm.

c) Prepare 0.1mol/L $FeCl_3$ solution and pour it into the electrolytic tank until it submerges the workpiece by 5-10mm. Clean both the workpiece and the tank after the machining process is completed.

d) Make observation and record of the results electrochemical drilling process using a scanning electron microscope.

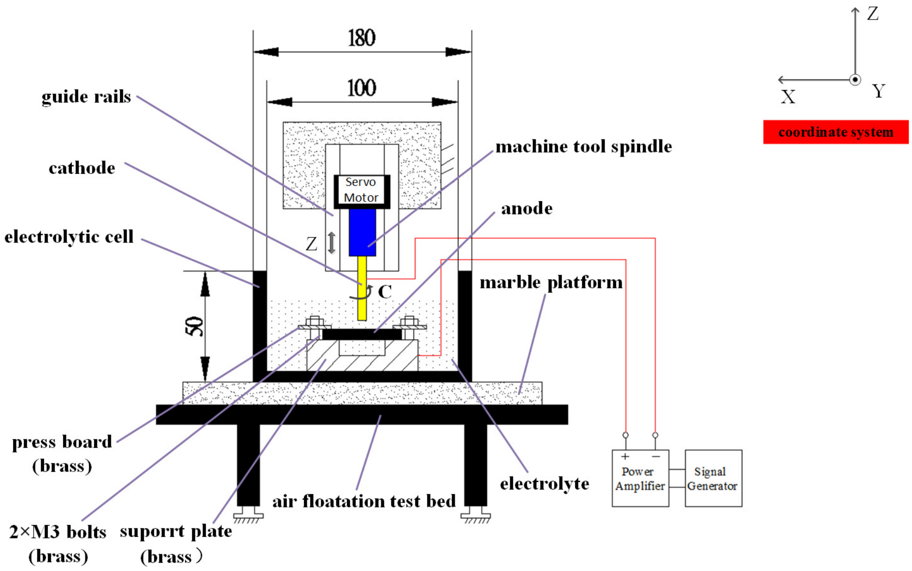

Fig.8. Experiment equipment

Table 2. Experiment parameters

Parameter	Value
anode	25×25×0.3mm 304SS
cathode	Φ1mm H62 Brass
electrolyte	$FeCl_3$
machining gap	0.12mm
cathode speed	6000r/min
voltage	10V

Figure 9 shows the workpiece after processing. As shown in the Figure 8, DC signal: the inlet diameter of the drilled workpiece is 1800.87μm and the outlet diameter is 1367.41μm; sinusoidal signal: the inlet diameter is 626.41μm and the outlet diameter is 1394.55μm; triangular signal: the inlet diameter is 1589.97μm and the outlet diameter is 1389.80μm; rectangular signal: the inlet diameter is 1490.23μm and the outlet diameter is 1115.17μm. Among the four signals, the machining accuracy of the DC signal is the lowest, while the rectangular pulse signal has the highest machining accuracy. The machining accuracy of the triangular signal is higher than that of the sinusoidal signal.

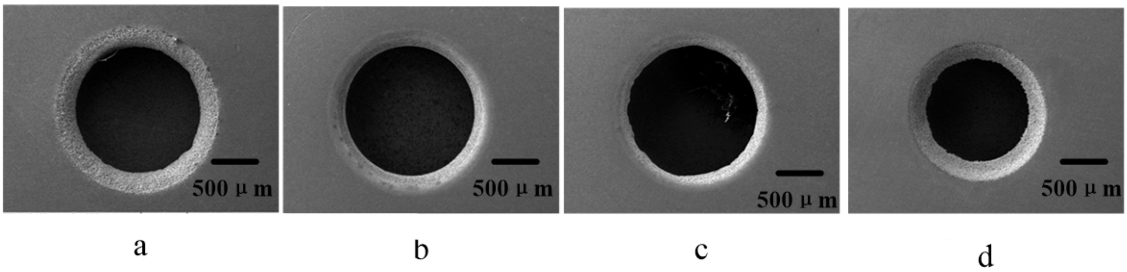

Fig. 9. experimental results (a. DC signal; b. sinusoidal signal; c. triangle signal; d. pulse signal)

5. Discussion

The experiment results are consistent with the simulation results, which proves that the dimensional accuracy of the hole drilled by using the rectangular pulse power is higher than those by using the DC, sinusoidal and triangular voltage signals. Under the same current efficiency and during one signal cycle (1e-4s), the valid machining time of the DC, sinusoidal and triangular voltage signals is also1e-4s, but the valid machining time of the rectangular pulse signal is less than 5e-5s because of the VIL-to-VIH and VIH-to-VIL variation generated by the rectangular pulse signal. From the areas obtained by integrating the current curves we see that: according to the amount of the supplied energy, the order of the four waveform signals is: DC, sinusoidal, triangular and rectangular.

It can be found from the measurement of the experiment results that, according to the dimensional accuracy of the drilled hole, the order of the four waveform signals is: DC, sinusoidal, triangular and rectangular. Moreover, from the analysis of the material removed per unit time we know that: among the four signals, the DC signal has the highest machining efficiency while the rectangular signal has the lowest machining efficiency, and the machining efficiencies of the sinusoidal and the triangular signals fall in between them. For practical machining, therefore, when a low machining accuracy or an efficient machining process is required, the sinusoidal or the triangular signal can be used for the ECM.

6. Conclusions

1. Different waveform voltage signals have different degrees of effect on the dimensional accuracy of the hole machined by the electrochemical drilling technology, and the order of the effect degrees is: DC signal, sinusoidal signal, triangular signal and rectangular pulse signal.
2. For the sinusoidal and the triangular signals, their machining accuracies are higher than that of the DC power, and their machining efficiencies are higher than that of the rectangular pulse signal. Therefore, they are suitable for workpieces without high requirements on machining accuracy and efficiency.
3. This work makes a little contribution for us to balance ECM’s efficiency and accuracy.

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