Multi-physics Coupling Simulation of Precise Electrochemical Machining (PECM) with Pulsed Current and Vibrating Cathode

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Abstract. A new multi-physics model is presented for numerical simulation of the precise electrochemical machining process with pulsed current and vibrating cathode. The method includes the change of electric field, flow field, temperature field and geometric deformation field. Meanwhile, the effects of cathodic vibration on electrolyte velocity is obtained by transient simulation of flow field and the velocity distribution obtained from the multi-step steady state flow field is compared with that of transient flow field. To solve the problem that machining process simulation needs a lot of computing time, a multi-step steady state flow field solution and a loop iterative solution algorithm based on COMSOL are presented, and the error analysis was carried out. The results show that the algorithm can ensure the error within a reasonable range and greatly reduce the calculation time.

1. Introduction
The PECM is an advanced ECM process developed on the basis of traditional DC-ECM and pulsed ECM [1]. The PECM process realize a high current density by adding a vibrating cathode movement which in turn leads to an increased accuracy and a decreased surface roughness. Electric pulses are only applied around the bottom dead center of the vibration while the larger working gap around the top dead center allows an improved electrolyte flow [2,3].

Due to the PECM involves electric field, flow field, temperature field, geometric deformation field etc. It is difficult to analyze the influence of the parameters of each field on the final anode surface [4,5,6]. Therefore, this paper mainly establishes the multi-physics coupling simulation model under the vibration condition and grasps its basic theory and the influence law through the dynamic simulation, which provides the theoretical basis for the cathode design and the parameter optimization in the actual processing.

2. Theoretical Model
The schematic diagram of PECM process is shown in the figure 1. The cathode is at the top and the anode is at the bottom. The electrolyte is pumped from left to right. The length of the anode is 35 mm and the height is 8 mm. The length of the cathode is 35 mm and the height is 10 mm.
2.1. Electrical model
The electrodes consist of a homogeneous piece of metal of which the electrical conductivity $\kappa$ is assumed constant. The potential distribution $V(V)$ is given by the law of charge conservation:

$$\nabla \cdot (\kappa \nabla V) = 0$$

(1)

A linearized temperature dependent model is used for the current density ($j_k$) of all the electrode reactions [7]:

$$j_k = \left[1 + \alpha (T - T_{ref})\right] \frac{V - U - Q_k}{R_k}$$

(2)

Where, $\alpha$ is a constant, $T_{ref}$ is the reference temperature, $R_k$ is the polarization resistance, $Q_k$ is the onset of polarization. $V$ is electrode potential, $U$ is electrolyte potential.

2.2. Flow Model
The experiment shows that only when the electrolyte reaches the turbulent state, the electrolyte can timely discharge the electrolyte products and heat from the gap, and the electrolytic processing can be performed stably. Without considering hydrogen precipitation, the electrolyte flow can be represented by the incompressible viscous flow Navier-Stokes equation [8]:

$$\begin{cases}
\rho \frac{\partial \vec{u}}{\partial t} + \rho (\vec{u} \cdot \nabla) \vec{u} = \nabla \cdot \left[-P I + (\mu + \mu_T)(\nabla \vec{u} + (\nabla \vec{u})^T)\right] \\
\rho \nabla \cdot (\vec{u}) = 0
\end{cases}$$

(3)

Where, $\vec{u}$ is the electrolyte flow rate, $P$ is the electrolyte pressure, $\mu$ is the dynamic viscosity of the electrolyte solution, $\rho$ is the density of the electrolyte, $\mu_T$ is the turbulent viscosity coefficient.

2.3. Thermal model
In the process of ECM, the heat of electrode mainly comes from the Joule heat of electrode and the reaction heat on the surface of the inner electrode. The Joule heat produced by the electrode is negligible compared with the heat generated on the surface of the inner electrode because of the high conductivity of the electrode. According to the law of conservation of energy, the transient equation of temperature can be obtained [9]:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (K \nabla T)$$

(4)
Where, $\rho$ is the density of electrode, $C_p$ is the electrode specific heat capacity, $K$ is the electrode heat transfer coefficient.

The law of electrolyte temperature distribution [10]:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \nabla T = \nabla \cdot (K \nabla T) + P_j$$  \hspace{1cm} (5)

Where, $\rho$ is the density of electrolyte, $C_p$ is the electrode specific heat capacity, $K$ is the electrode heat transfer coefficient, $P_j$ is the heat generated in the electrolyte bulk solution.

Joule heating is considered and obtained by Joule’s law as:

$$P_j = E \cdot j$$  \hspace{1cm} (6)

Where, $j$ is the current density, $E$ is the electric field.

2.4. Moving mesh model

The moving mesh method is used to solve the problem of vibration feeding and anodic corrosion geometric deformation.

2.4.1. Cathode vibrate feed. The vibrational form of the cathode is sinusoidal wave, and the feed velocity of the cathode ($v_c$) is 0.4mm/min. The velocity of cathode motion is:

$$v = v_c + A \cos \omega t$$  \hspace{1cm} (7)

Where, $A$ is the amplitude, $\omega$ is the angular frequency.

2.4.2. Anode dissolution.

The anode removal rate $v_a$ can be calculated using Faraday’s law [8]:

$$v_a = -\eta \frac{j_a M}{zF \rho}$$  \hspace{1cm} (8)

Where, $\eta$ is the Current efficiency, $j_a$ is the anode reaction current density, $z$ is the valence number of ion, $F$ is Faraday constant, $M$ is the molar mass and $\rho$ is the density of electrode.

3. Multi-physics Coupling Simulation

The coupling relations among the physical fields in PECM are shown in figure 2.

![Figure 2. The couplings between the physical fields.](image-url)
3.1. Simulation Parameters
Aqueous 250g/l NaNO₃ electrolyte solution is pumped through the channel from left to right. The specific simulation parameters of flow field are shown in Table 1. A potential difference of 15V is applied between the upper cathode and lower anode surface, and the pulse frequency is 50Hz. The polarization parameters for the electrode reactions are shown in Table 2. The ambient and electrolyte inlet temperature is 20°C.

| Initial value | Inlet | Outlet | Vibration | Wall |
|---------------|-------|--------|-----------|------|
| $U_0$         | 0m/s  |        |           |      |
| $P_0$         | 0MPa  |        |           |      |
| $P_{in}$      |       | 0.6MPa |           |      |
| $U_{ref}$     | 1m/s  |        |           |      |
| $P_{out}$     | 0.1MPa|        |           |      |
| $A$           | 0.1mm |        |           |      |
| $\omega$      | 100   |        |           |      |
| $\eta_4$      | $\pi$ |        |           |      |
| $\eta_{13}$   | other |        |           |      |

The polarization parameters of electrode materials in NaNO₃ solution are shown in Table 2 [7].

| Electrode | Polarization resistance($\Omega \cdot m^2$) | Equilibrium potential (V) |
|-----------|---------------------------------------------|----------------------------|
| cathode   | $1 \times 10^{-7}$                        | -1                         |
| anode     | $3 \times 10^{-6}$                        | 2.2                        |

3.2. Solution Approach
Electrolyte flow rate is the key variable to realize the coupling of flow field and temperature field. In the process of PECM, the position of the cathode varies with time, that is, the gap between the poles varies with time. Therefore, the transient solution of the electrolyte flow velocity under the vibration condition should be used to simulate the temperature evolution of the electrolyte in the simulated working gap. However, it takes a lot of time to solve the transient flow field in a unit period, and it is not acceptable to simulate the temperature for a long time by using the transient solution of the flow field. Therefore, it is necessary to find a simplified algorithm to solve the flow field.

3.2.1 Multi-step steady state solution.
The geometric changes at different times can be obtained by solving only the moving mesh model and not the flow model. The stationary solution of flow field is added to the study again, and the geometric structure obtained by transient solution is added to the stationary solution of flow field to obtain the electrolyte velocity distribution under different gaps.

3.2.2 Loop iterative solution algorithm.
The velocity distribution in the multi-step steady state of the flow field under the vibration condition is similar to the result obtained by the transient solution, considering the high time efficient of the multi-step steady state solution. The electrolyte velocity between time $t$ and $t+\Delta t$ is assumed to be approximately invariant by time discretization, that is, the steady velocity distribution at $t$ moment is regarded as the velocity distribution in $\Delta t$ time interval. After the electrolyte velocity distribution is obtained, the velocity is regarded as input variable into transient solution includes the secondary current distribution, the transient solution of fluid heat transfers and moving mesh. Finally, the temperature distribution in the processing area is obtained.

A new solution algorithm based on COMSOL is presented for reduce the simulation costs. Two studies were added to the multi-physics coupling model, each of which takes a calculation period as an example. The number of steps for a multi-step steady-state solution is $n$, then the time step of the solution is $T/n$. The solver time for transient calculations is set to $range((i-1)T/n,T/(2n),iT/n)$. When the solution of study 1 is completed, the result of the last step is passed to the first step of study 2 by setting the dependent variable. The results of the last step will also be passed to the first step of
study 1 after the completion of the calculation of study 2, thus completing the entire iterative process of the cycle. The loop iterative solution algorithm based on COMSOL is shown in figure 3.

4. Results and discussion

4.1. Flow evolution
The transient solution of the variation of flow rate with time at five reference points on the anode surface during the unit period are shown in figure 4. It can be seen that the velocity of electrolyte increases with the increase of working gap in a single cycle. At point 1 and 5, the continuity of velocity with time is poor, and the fluctuation is obvious, but the fluctuation law basically meets the law of velocity variation inside the channel.

The multi-step steady state solution of flow rate with time at five reference points on the anode surface during the unit period are shown in figure 5.
Figure 5. The comparison of speed at different reference points.

4.2. Temperature evolution

The transient solution of the variation of temperature with time at five reference points on the anode surface during the unit period are shown in figure 6. The temperature of the entrance of the working gap is almost constant during the whole period, keeping the same temperature as the ambient temperature. The temperature of each reference point reaches the peak at about 0.007s, which is due to the small working gap and the high current density, so the heat produced by PECM can’t be taken away in time. The temperature of the second half period drops sharply when the pulse power is turned off, the cathode is raised up and the gap is enlarged and the heat transfer effect of the fluid is shown. At the end of the period, the temperatures at each point are higher than at the beginning.

The transient solution of the variation of temperature with flow channel at different times points on the anode surface during the unit period are shown in figure 7. As direction of the flow field increases, the temperature of each reference point on the anode surface generally exhibits an upward trend. During the period of pulse opening, the temperature of outlet increased slightly due to the decrease of electrolyte flow rate and the phenomenon of temperature reflux. The temperature at the outlet begins to decrease when the processing is at the pulse off time, because there are enough electrolytes in the right chamber for convection heat transfer. It also shows that the first half of the period is mainly electrochemical reaction and the second half is the convection heat transfer of electrolyte during the whole vibration period.

The temperature evolution of each reference point on the surface of the anode in 20 cycles was obtained by the loop iterative solution algorithm. Figure 8 presents the temperature at the end of the cycle is higher than it was at the beginning, and the average temperature in a single period is also increasing, which indicates that the temperature in the gap accumulates with the passage of time.
Figure 8. The temperature evolution over 20 cycles at different reference points.

As shown in figure 9, the variation of temperature with time at four reference points on the anode surface during the unit period was obtained by the loop iterative solution algorithm. Case 1 represents the transient solution of the variation of temperature. The number of steps of multi-step steady state solution in case 2 is 2, and the time of unit cycle solution is about 4 min. The number of steps of multi-step steady state solution in case 3 is 5, and the time of unit cycle solution is about 9 min. The number of steps of multi-step steady state solution in case 4 is 10, and the time of unit cycle solution is about 18 min. With the increase of the number of steps of multi-step steady state solution, the temperature fluctuation is more consistent with the temperature fluctuation obtained by the transient solution, but the solution time also increases.

4.3. Result analysis of multi-step steady state solution

As shown in figure 10, the relative error of multi-step steady state solution of the variation of temperature with time at four reference points on the anode surface during the unit period. In case 2, the maximum relative error exceeds 30%, which beyond the allowable range of error. When the number of steps \(n\) is equal to 10, the maximum relative error is less than 13% and the calculation time is reduced from 20 h to 18 min, which is of great significance for long time simulation.
5. Conclusion
A new Precision Electrochemical Machining (PECM) model based on COMSOL Multiphysics was presented, which takes into account of the change of electric field, flow field, temperature field and geometric deformation field in PECM. The conclusions can be summarized as follows:

1) Under the condition of vibration feed, the electrolyte velocity increases with the increase of working gap.
2) The electrolyte velocity distribution obtained by multi-step steady state solution is similar to that obtained by transient solution.
3) The loop iterative solution algorithm based on COMSOL is presented for reducing the simulation costs. When the number of steps n is equal to 10, the maximum relative error is less than 13% and the calculation time is reduced from 20 h to 18 min, which is of great significance for long time simulation.

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