Design and Analysis of Flow Field in Electrochemical Machining of Micro Grooves on Gear Tooth Surface

Yuanlong Chen¹, a, *, Tengfei Zhang¹, b, Hua Lin¹, Qi Chen¹

¹School of Mechanical Engineering, Hefei University of Technology, Hefei 230009, China
²chenyuanlong@hfut.edu.cn, ³1831766842@qq.com

Abstract. The gear with solid lubricating material embedded in micro grooves on gear tooth surface can better adapt to severe lubrication conditions. Electrochemical machining with the mask has shown good feasibility in machining micro grooves for filling solid self-lubricating materials on the tooth surface of gear. The electrolyte flow field is a vital contributor to the accuracy of electrochemical machining, therefore, it is important to design a suitable electrolyte flow mode. In this paper, based on the distribution characteristics of micro grooves on gear tooth surface, two kinds of shaped cathodes are designed, one with electrolyte flow slot and the other without. Each cathode can form two electrolyte flow modes respectively. The effects of four electrolyte flow modes on the stability of the machining gap flow field are analyzed by using computational fluid dynamics. The simulated results show that the cathode without electrolyte flow slot is beneficial to electrolyte flow during electrochemical machining with the mask, notably when the electrolyte flows into the machining gap from the face of the gear.

1. Introduction
In view of the deficiency of present self-lubricating gear technology, Chen et al. proposed a new type of self-lubricating gear [1]. The salient feature of the gear is that staggered micro-grooves for filling solid self-lubricating materials are machined on the gear tooth surface. Depending on the excellent lubrication characteristics of filling materials, this new type of gear can better adapt to harsh conditions of insufficient lubrication.

At present, various methods have been researched for the fabrication of micro grooves, such as laser processing, electrical discharge machining and electrochemical machining (ECM) [2, 3]. Among them, ECM is a metallic anodic dissolution process in which the metallic workpiece and tool are separately the anode and cathode [4]. The major advantages of ECM are high removal rate in combination with the damage-free of workpiece surface [5]. Liu et al. proposed a method of ECM using multifunctional cathode to machine micro grooves on workpiece with the width of 0.7 mm and the depth of 0.46 mm [6]. In ECM with the mask, metal is dissolved from unprotected areas of a mask-patterned workpiece that acts as the anode in an electrolytic cell [7]. Xu et al. fabricated micro grooves on SS304 metal surface with the width of 0.25 mm and the depth of 0.1 mm by employing ECM with the mask [8]. However, research on electrochemical machining of micro grooves on involute tooth surface of gear is still deficiency.

In this paper, according to the distribution features of micro grooves on gear tooth surface, two kinds of shaped cathodes are designed, one with electrolyte flow slot and the other without. Each cathode can form two electrolyte flow modes separately. In order to obtain the most reasonable electrolyte flow mode for ECM with the mask. The flow field distribution in the machining gap of those four flow modes are

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
analyzed by computational fluid dynamics.

2. The Principle of ECM with the Mask Using Shaped Cathode
The research object of this paper is involute spur gear with the module is 2mm and the tooth thickness is 15mm. The width and depth of micro grooves can be calculated to be 0.38 mm and 0.16 mm respectively. The grooves are distributed on the involute tooth surface. In ECM with the mask, micro-patterns can be produced on photoresist-coated workpiece using photolithography, the metal is then selectively dissolved from the unprotected regions, so the method has high feasibility.

The paper adopted the shaped cathode of single-tooth method for the tool cathode design. The shape of cathode is designed based on the shape of gear tooth space, but the overall reduction is 0.3 mm compared with the spacewidth, this gap is used for electrolyte flow [9]. Figure 1 shows a schematic diagram of ECM with the mask using shaped cathode. The workpiece is covered by the photoresist mask with micro grooves pattern. The area of the workpiece exposed to the electrolyte can be dissolved when in an energized state. The dissolved metal, the Joule heat produced and the generated gas bubbles are carried away by flowing electrolyte.

![Figure 1. Schematic diagram of the ECM with the mask using shaped cathode.](image)

3. The Design of Cathode and Flow Mode
The micro grooves studied in this paper are mainly distributed on the involute tooth surface of the gear, and there is no distribution at the bottom of the gear tooth space. Based on the feature, two kinds of shaped cathodes are designed, one with electrolyte flow slot and the other without. As shown in figure 2(a), the kind of cathode is called the shaped cathode with electrolyte flow slot. In the middle of the cathode, there is a channel for the electrolyte to flow into the machining gap. The shaped cathode with electrolyte flow slot as shown in figure 2(b). The cathode does not directly participate in the supply of electrolyte, and the flow mode of electrolyte is lateral flow.

![Figure 2. Shaped cathode model.](image)

The flow mode of electrolyte depends on the design of the cathode and the shape of the workpiece. Four electrolyte flow modes were proposed. Among them, Mode-I and Mode-II are composed of cathode with electrolyte flow slot and workpiece, Mode-III and Mode-IV are composed of cathode without electrolyte flow slot and workpiece. As shown in figure 3(a), the kind of flow mode is called Mode-I in...
which the electrolyte flows from the inlet on the cathode into the machining gap, and flows out of the machining gap from the electrolyte outlet. As shown in figure 3(b), the electrolyte flow path of Mode-II is opposite to that in Mode-I. As shown in figure 3(c), the electrolyte in Mode-III flows from the inlet at the gear tooth tip into the machining gap and then flows out from the outlet. From figure 3(d), it is clear that the electrolyte in Mode-IV flows into the machining gap from the face of the gear. To obtain the most suitable flow mode, a computational fluid dynamics (CFD) will be carried.

![Figure 3](image)

**Figure 3.** Schematic diagram of the electrolyte flow mode.

### 4. Numerical Simulation of Electrolyte Flow Field

The flow field is the interspace between the cathode and the workpiece, which is determined by the design of the electrolyte flow mode and the shape of the workpiece. Since the object of the study is the flow field in the machining gap, the micro grooves and mask are not considered during modeling. The flow field model of Mode-I and Mode-II is show in figure 4(a). In the model, the plane A in the middle of the cathode is the inlet or outlet of the electrolyte. Figure 4(b) shows the flow field model of Mode-III and Mode-IV.

![Figure 4](image)

**Figure 4.** Geometric model of flow field simulation.

### 4.1. Mathematical Model

The simulation is based on following assumptions: (1) the fluid is an incompressible, continuous, and viscous Newtonian fluid. (2) The change of the electrolyte temperature and the energy dissipation caused by the temperature differences are ignored, and the flow motion obeys the mass and momentum conservation equations which can be written as

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

Where \( \mathbf{u} \) is the velocity vector along the \( x \)-axis, \( P \) is the mean electrolyte pressure, \( \mu \) is the dynamic viscosity, \( \rho \) is the density of the fluid, and \( \mu_T \) is the turbulent viscosity coefficient.

The obvious improvements of the RNG \( k - \varepsilon \) model compared with the standard model is due to the
better treatment of near-wall turbulence effects [10]. In the ECM process, the electrolyte is sealed in the fixture, the flow in the machining gap is complex, and the electrolyte streamlines are curved. Thus, the RNG $k-\varepsilon$ model is suitable for the current situation and is adopted in this paper to simulate the flow field. The equations are as follows:

\[
\frac{\partial (\rho \kappa)}{\partial t} + \frac{\partial (\rho \kappa u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right] + G_k + \rho \varepsilon \tag{2}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{C'_\varepsilon \varepsilon}{k} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \tag{3}
\]

Where $\kappa$ is turbulent kinetic energy, $\varepsilon$ is dissipation rate, $G_k$ is turbulent kinetic energy caused by gradient change, the model constants are given as $C_\mu = 0.0845$, $C_{1\varepsilon} = 1.42$, $C_{2\varepsilon} = 1.68$, and $\alpha_k = \alpha_\varepsilon = 1.39$.

4.2. Numerical Simulation Results and Analysis

Based on the RNG $k-\varepsilon$ turbulent model, the flow field simulation in the machining gap is carried out employing the ANSYS software. The boundary conditions determined by initial work are that the electrolyte inlet pressure is 0.4 MPa and the outlet pressure is 0.1 MPa. After simulation, the pressure and velocity distribution of electrolyte in the machining gap of Mode-I and Mode-II can be obtained, as shown in figure 5. Mode-I, the simulation results show that the electrolyte pressure in the machining gap is low as a whole, and there are negative pressure areas near the bottom of the cathode. The electrolyte flow forms a vortex in the negative pressure area, which will lead to defects such as flow marks or grooves on the machined surface. In Mode-II, the electrolyte pressure is relatively uniform as a whole. However, the electrolyte pressure in the flow channel is high, resulting in a low electrolyte flow velocity on the machining surface. The electrolytic products will be hard to remove because of the low velocity. Based on the above description and the simulation results, the flow field uniformity of Mode-I and Mode-II is poor.

![Figure 5. Electrolyte pressure and velocity distribution in the machining gap.](image-url)
When the electrolyte flows in Mode-Ⅲ and Mode-Ⅳ, the velocity and pressure distribution of the flow field in the machining gap are shown in figure 6. In Mode-Ⅲ, gradient change of electrolyte pressure in the machining gap, the electrolyte flow velocity is relatively uniform as a whole. However, because the flow path is curved, the electrolyte flow at the bottom of the machining gap is confused. In Mode-Ⅳ, the electrolyte pressure changes in gradient and the flow velocity distribution is uniform.

![Image](a) Pressure of Mode-Ⅲ  (b) Velocity of Mode-Ⅲ  
![Image](c) Pressure of Mode-Ⅳ  (d) Velocity of Mode-Ⅳ

**Figure 6.** Electrolyte pressure and velocity distribution in the machining gap.

In order to get the best flow mode of the electrolyte. The velocity curves of Mode-Ⅲ and Mode-Ⅳ are obtained as shown in figure 7. As figure 7(a) shows, In Mode-Ⅲ, the flow velocity of the electrolyte fluctuates greatly, and the uniformity of the flow field is poor, which will seriously affect the stability of the ECM process. For Mode-Ⅳ, as described in figure 7(b), the electrolyte flow velocity is relatively uniform without large fluctuations. It indicates that the flow field distribution of this mode is uniform.

![Image](a) Velocity curves of Mode-Ⅲ  (b) Velocity curves of Mode-Ⅳ

**Figure 7.** Velocity curves of electrolyte under Mode-Ⅲ and Mode-Ⅳ.

### 5. Conclusions

The electrolyte flow field is a critical factor that affects processing stability and surface quality during ECM with the mask. In this paper, the ECM with the mask using shaped cathode has been adopted to
fabricate micro grooves on the gear tooth surface. Four electrolyte flow modes consisting of the shaped cathode have been simulated by means of a finite element fluid analysis method. The simulated results have indicated that the cathode without electrolyte flow slot was beneficial to electrolyte flow during ECM with the mask, especially when electrolyte flows into the machining gap from the face of the gear.

Acknowledgement
This work is financially supported by the National Natural Science Foundation of China (51775158).

References
[1] Chen Q, Yao Z G, Xu F, Li H 2017 CN Patent 106678347 A.
[2] Schreck S, Gahr K H Z 2005 Laser-assisted structuring of ceramic and steel surfaces for improving tribological properties, J. Appl. Surf. Sci. 247 616-22.
[3] Uhlmann E, Piltz S, Doll U 2005 Machining of micro/miniature dies and moulds by electrical discharge machining—Recent development, J. Mater. Process. Technol. 167 488-93.
[4] Bhattacharyya B, Munda J, Malapati M 2004 Advancement in electrochemical micro-machining, J. Int. Mach. Tool. Manuf. 44 1577-89.
[5] Lohrengel M M, Rataj K P, Münninghoff T 2016 Electrochemical Machining - Mechanisms of anodic dissolution, J. Electrochim. Acta. 201 348-53.
[6] Liu G X, Zhang Y J 2017 The tool design and experiments on PECM of micro channel arrays on metallic bipolar plate using multifunctional cathode, Int. J. Adv. Manuf. Technol. 89 407-16.
[7] Kern P, Veh J, Michler J 2007 New developments in through-mask electrochemical micromachining of titanium, J. Micromech. Microeng. 17 1168-77.
[8] Xu W J 2015 Experimental Study on ECM of Microgrooves, Electromachining. Mould, 1 3-6.
[9] Zhou J J, Pang G B 2009 Design of Flow Field for Finishig Spiral Bevel Gear in Pulse Electrochemica Finishing, China Mech. Eng. 20 1425-32.
[10] Wang F J 2004 Computational fluid dynamics analysis, Tsinghua University Press, Beijing.