Analysis and Optimization of Flow Field in Electrochemical Machining of the staggered groove on Gear Tooth Surface

Yuanlong Chen\textsuperscript{1,*}, Zihao Huang\textsuperscript{1,b}, Hua Lin\textsuperscript{1}, Qi Chen\textsuperscript{1}

\textsuperscript{1}School of Mechanical Engineering, Hefei University of Technology, Hefei 230009, China
\textsuperscript{a}chenyuanlong@hfut.edu.cn, \textsuperscript{b}1252392948@qq.com

Abstract. Self-lubricating gears can better adapt to the bad lubrication conditions without oil or oil scarcity. Staggered groove can be produced by Electrochemical machining (ECM) on the gear tooth surface to fill solid lubricating materials. The cathode with and without flow slot has been designed. Three basin models have been established which are forward flow mode, reverse flow mode and side flow mode. The gap flow field of ECM has been analyzed. It is determined that positive flow is a suitable flow mode. By optimizing the structure of the flow slot in the cathode, the deficiency of the forward flow field is improved.

1. Introduction
In recent years, surface texture has been widely used in reducing friction, improving lubrication and increasing bearing capacity\textsuperscript{[1]}. Grooves, as a form of surface texture, have been widely used in many fields. Chen Qi et al. found that texture can construct cross-scale self-lubricating interface on the surface of gears to improve the lubrication of gears and make gears have a certain degree of hardness and smoothness\textsuperscript{[2]}.

At present, the common methods of groove machining are laser Beam Machining, micro-cutting, electrical discharge machining, ECM, etc. ECM has the advantages of flexible processing, no loss of cathode and high processing efficiency. Chen Wei et al. machined multi-channel slots with the width of 0.5 mm and the depth of 0.3 mm on stainless steel sheets and provided the reference processing parameters\textsuperscript{[3]}. Han Lijun provided a scheme of sidewall insulation for electrochemical processing of groove\textsuperscript{[4]}.

The uniformity design of flow field is particularly important to ensure the accuracy of ECM. In the process of electrochemical machining, the flow of electrolyte should be sufficient and uniform at all parts of the working surface in the machining gap, and streamline intersection and other flow field defects should not occur. Otherwise, some defects such as flow liner may occur on the working surface, which will affect the processing accuracy and surface quality. Seriously, short circuit may occur and damage cathode and workpiece\textsuperscript{[5]}. The flow field depends on the shape of the cathode and the structure of the flow-path. Therefore, in order to obtain a suitable flow field, the cathode and the flow-path must be studied accordingly\textsuperscript{[6]}.

2. The principle of Computational Fluid Dynamics
Computational fluid dynamics (CFD) is the analysis of a system containing physical phenomena such as fluid flow and heat conduction by means of computer numerical calculation and image display\textsuperscript{[7]}.

In this paper, the electrolyte flow path in the process of machining is selected as the research object,
and the CFD method is used to simulate the flow field, and the different flow fields are analyzed.

3. The design of three-dimensional model and the cathode
The research object is a tooth of involute spur gear with the module of 10, the tooth thickness is 40mm, the number of teeth of 18 and the pressure angle of 20°. The shaped cathode is constructed by an equidistant solid method. The three-dimensional model is shown in Figure 1.

![Figure 1. The physical model](image)

According to the characteristics of the flow field, the cathode is divided into two kinds. The first type of cathode has a cross type flow slot inside the cathode. And the second is that is no flow slot inside the cathode, as shown in Figure 2-3.

![Figure 2. The cathode with flow slot](image)

![Figure 3. The cathode without flow slot](image)

3.1. Numerical simulation of electrolyte flow field
There are three flow modes of electrolyte: side flow mode, forward flow mode and reflux flow mode. The simulation model is shown in Figure 4-6. Fluent is used to simulate and analyze these three methods.

![Figure 4. The calculation model of side flow mode](image)

![Figure 5. The calculation model of forward flow mode](image)

![Figure 6. The calculation model of reflux flow mode](image)
3.2. Mathematical model

Because the electrolyte in the runner is steady-state analysis, the following assumptions are made in the process of modeling: (1) the fluid is incompressible and constant Newtonian fluid (the dynamic viscosity remains unchanged when the velocity gradient changes)\(^8\); and (2) the electrolyte flow is required to be turbulent in electrolytic processing. Considering the neglect of the change of working medium temperature and the energy dissipation caused by temperature difference, the flow should be constrained by the mass conservation equation and the momentum conservation equation\(^9\).

For incompressible flows, the following mass and momentum conservation equations can be used to describe them:

\[
\begin{align*}
\nabla \cdot \vec{v} &= 0 \\
\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} &= -\frac{1}{\rho} \nabla p + \mu \nabla^2 \vec{v}
\end{align*}
\]

(1)

Where \(\vec{v}\) is Velocity vector, \(P\) is pressure, \(\rho\) is density, \(\mu\) is dynamic viscosity.

Turbulent dissipation rate, \(\epsilon\), has practical physical significance, so model \(k-\epsilon\) has been widely used in practical engineering\(^{10}\). The accuracy of RNG \(k-\epsilon\) model is better than that of standard \(k-\epsilon\) model, so RNG \(k-\epsilon\) model is adopted in this paper. The corresponding \(k\) equation and \(\epsilon\) equation are as follows:

\[
\begin{align*}
\frac{\partial(\rho \kappa)}{\partial t} + \frac{\partial(\rho \kappa u_i)}{\partial x_i} &= \frac{\partial}{\partial x_j} \left[ \alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right] + G_k + \rho \epsilon \\
\frac{\partial(\rho \epsilon)}{\partial t} + \frac{\partial(\rho \epsilon u_i)}{\partial x_i} &= \frac{\partial}{\partial x_j} \left[ \alpha_\epsilon \mu_{eff} \frac{\partial \epsilon}{\partial x_j} \right] + \frac{C_{\mu} \epsilon}{k} G_k - C_{2\epsilon} \rho \frac{\epsilon^2}{k}
\end{align*}
\]

(2)

(3)

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

The wall function method is used to simulate the flow in the near wall region.

3.3. Mesh generation and boundary condition setting

Basin is imported into mesh module developed by ANSYS to grid generation. In order to better simulate the flow of fluid in the boundary layer, the expansion layer is used to mesh the wall. To increase the reliability of the results and make the best use of the computer performance, the edge control feature-based control grid is selected to refine the edge grid. The method of mesh generation for the three kinds of electrolyte flow models is the same. The mixed grids of hexahedron and tetrahedron are used for partition, and the wall function method is used for approximate calculation. The computational area grid model is shown in Figure 7.

![Figure 7. The computational area grid model](image)
The boundary conditions are determined as follows: the turbulent model, RNG $k-\varepsilon$, is solved. And the inlet pressure $P_1=0.4\text{MPa}$. Kinematic viscosity coefficient of water $v=1.01\times10^{-6}\text{m}^2/\text{s}$. Simple algorithm of coupled control equation with pressure based separate solver and implicit speed algorithm. Liquid material select liquid water.

4. Numerical simulation results and analysis.

Figure 8-9 show the pressure contour and velocity vector diagram of the side flow field in the processing area at steady state. It can be seen from the results that when electrolyte flows to the cathode, most of the electrolyte flows to both sides of the cathode, and few of the electrolyte flows to the processing area of the positive center, and the pressure distribution at both ends of the cathode is quite different. The flow uniformity of the field is poor.

Figure 8. Pressure contour

Figure 9. Velocity vector

Figure 10-11 show the pressure contour and velocity vector diagram of the reflux flow field in the processing area at steady state. It can be seen from the results that when the electrolyte enters the machining gap at the same time from the liquid inlet on both sides, the electrolyte will be blocked by the cathode like the current measuring type, and most of the electrolyte is been offset, resulting in a small flow rate of electrolyte outside the cathode.

Figure 10. Pressure contour

Figure 11. Velocity vector

Figure 12-13 show the pressure contour and velocity vector diagram of the forward flow field in the processing area at steady state. It can be seen from the results that the flow rate and pressure of electrolyte from the inlet to the outlet drop rapidly. When the electrolyte enter the processing gap from the cathode through the flow slot at a high flow rate, most of the electrolyte returns along the liquid tank after hitting the cathode due to the right angle between the processing area and the flow slot. This results in a large electrolyte pressure and a small electrolyte flow rate in the flow slot, especially in the center of the flow slot.

Figure 12. Pressure contour

Figure 13. Velocity vector

Comparing the velocity vector diagram of forward flow and reverse flow, it is found that the flow velocity of electrolyte decreases obviously in the flow slot. We take the reverse flow type and forward
flow type at the diagonal of the processing area as the object to study the flow rate change, and make the flow rate change curve as shown in Figure 14 and 15. It can be seen that the speed of forward flow and reverse flow decreases sharply at the center and both sides of the machining area. The reflux flow field and the forward flow field have their own advantages and disadvantages, but the velocity fluctuation of the forward flow field is better than the reflux flow field, and the design difficulty of the forward flow field tooling is lower than that of the reflux flow field. Therefore, the forward flow field is more suitable for processing staggered grooves on the tooth surface.

![Figures 14 and 15](image1.png)

**Figure 14.** Velocity curves of reflux flow field  
**Figure 15.** Velocity curves of forward flow field

In this paper, the forward flow type is chosen as the flow form of electrolyte. But the flow field effect of the cross flow slot inside cathode is not good, the next step is to optimize the structure and distribution of the liquid tank in the cathode.

5. **Optimization and analysis of liquid tank in cathode**

The flow field in the machining gap is not ideal under the condition of forward flow of the cathode electrolyte with cross flow slot. In order to optimize the gap flow field, it is necessary to optimize the inlet structure of electrolyte, i.e. the flow slot.

The two improved cathode structures are shown in Figure 16-17. The first is the cathode with four independent flow slots, and the second is the cathode structure with four independent flow slots and a flow hole.

![Figures 16 and 17](image2.png)

**Figure 16.** Cathode with independent flow slots  
**Figure 17.** Cathode with independent flow slots and a flow hole

The grid division and boundary condition setting of the two kinds of gap flow field are the same as that of the cross flow slot cathode machining gap flow field. The pressure contour and velocity vector diagram of the fluid in the two machining gaps are analyzed.

Figure 18-19 show the pressure contour and velocity vector diagram of the cathode with independent flow slots in the processing area at steady state. It can be seen from the results that electrolyte flow out of flow slots and then accumulates to the center, where the flow lines intersect. The electrolyte flow at the corresponding place is disordered, which leads to the low flow rate at the center and the high pressure of the electrolyte.
6. Conclusions

In this paper, according to the structural characteristics of spur gear tooth surface and the technological characteristics of ECM, three geometric models of electrolyte flow in the cross groove of gear tooth surface have been designed, and the flow field (side flow, forward flow and reverse flow) has been simulated by ANSYS CFD software. According to the pressure contour and velocity vector diagram. The results show that the flow field in the machining gap of the cathode structure with four independent flow slots and a flow hole is better than that of the cathode with four independent flow slots and the cathode with cross flow slot.

Acknowledgement
This work is financially supported by the National Natural Science Foundation of China (51775158) and (51775161).

References
[1] L.P. Tang, Y. Chen, Influence of surface micro-texture on the tribological properties of heavy-duty gears, J. Journal of Tsinghua University (Natural Science Edition). 2010,50(07):1009-1012+1017.
[2] Q. Chen, Z.G. Yao, F. Xu and H. Li, CN Patent 106678347 A. (2017)
[3] W. Chen, μ s-Grade Adjustable Pulsed Power Supply & EMM Application, J. Mechanical Engineer. 2007(10):118-119.
[4] L. Q. Han, Electrolytic Machining of Deep and Narrow Slots, J. DIE & MOULD INDUSTRY. 1999(12):45-46.
[5] J.W. Xu, Numerical Simulation of Flow Field of NC-Electrochemical Contour Evolution Machining Based on CFD, J. Journal of System Simulation, 2009,21(01):73-75.
[6] W.J. Xu, Experimental Study on ECM of Microgrooves, Electromaching. Mould, 1(2015)3-6.
[7] F.J. Wang, Computational Fluid Dynamics Analysis--Principle and Application of CFD Software. M. Beijing: The tsinghua university press.2004
[8-9] John D. Anderson. Gasdynamic lasers : an introduction[M] Academic Press, 1976
[10] X.H. Liu, J. Ke, CFD Study on Temperature Field of Radial Clearance of Hydraulic Slide Valve, J. Chinese Journal of Mechanical Engineering .20 (2009) 1425-1432,2006(S1):231-234