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A Three-Dimensional FEM Model of Channel Machining by Scanning Micro Electrochemical Flow Cell and Jet Electrochemical Machining

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Highlights

- A three-dimensional finite element method model based on Faraday's law and moving mesh technique is proposed to describe the channel machining process by scanning micro electrochemical flow cell and jet electrochemical machining.
- The key to the simulation model is the introduction of the (virtual) thin electrolyte layer.
- Validation from the experiments and literature is conducted.

Abstract

In this research, a three-dimensional (3D) finite element method (FEM) model based on Faraday's law and moving mesh technique is proposed to simulate the channel machining process in Scanning Micro Electrochemical Flow Cell (SMEFC) and jet electrochemical machining (jet-ECM). The scarcity of available FEM models for the channel fabrication by electrochemical machining (ECM) with confined electrolyte is identified through a brief review of ECM simulation with moving electrode. The detailed information on the model establishment is then presented, including the fundamental principle, the way to construct the geometrical model of the moving electrolyte droplet during the machining process, the boundary settings and some key assumptions. Thanks to the introduction of the virtual electrolyte layer and the moving mesh technique, confined machining of channels by SMEFC can be simulated. In the experimental validation phase, species of the electrolyte (NaNO_3 and NaCl), the dimension of the hollow electrodes and the electrochemical equivalent of the workpiece, the machining voltages and feed rates are compared in terms of the channel cross-sectional profiles and errors. The flow field and heat transfer still need to be considered in order to simulate the case with NaNO_3 electrolyte in the future. This proposed 3D simulation model can improve the understanding and applicability of channel machining by SMEFC, since the current density distribution and the change of workpiece shape can be calculated simultaneously. With some modifications, this method can be as well extended to the channel machining by jet-ECM. Two case studies of micro scale and meso scale jet-ECM are simulated respectively. The proposed simulation method

is a potential way to understand and improve the channel machining process by ECM with confined electrolyte.

Keywords: Electrochemical machining (ECM); Scanning micro electrochemical flow cell (SMEFC); Channel machining; Simulation; jet electrochemical machining (jet-ECM)

1 Introduction

Electrochemical machining has attracted high attention from research and industry because of its capability in machining difficult-to-cut materials and the ability to separate the surface quality and the material removal rate [1]. There are several variants of ECM, such as sinking ECM [2], ECM milling [3], ECM wire cutting [4], ECM turning [5] and jet-ECM [6, 7]. Due to its machining flexibility, ECM also provides new possibilities for fabrication of holes with complex internal features through controlling the conductive area [8] and on-line adjusting the machining parameters [9]. Different from these variants, the Scanning Micro Electrochemical Flow Cell (SMEFC) method has recently been investigated as a near dry ECM method [10-12], featuring the elimination of electrolyte splashing and the potential to be integrated into other processing chains.

In the reported work [11], initial experiments of channel machining by SMEFC under constant-current mode have been carried out. The effects of current, feed rate, inter-electrode gap (IEG) and vacuum gap (VG) on the machining performance have been investigated. However, there is still no effective method to simulate the grooving process considering the real-time anode deformation. As a result, it is difficult to predict the cross-sectional profile of the channel and surface quality before the actual experiment, which hinders its further applications.

In this investigation, a 3D FEM simulation model is proposed and it enables the prediction of the machined channel cross-sectional profiles. The research status of the modelling of moving electrode in ECM is summarized. The 3D FEM simulation model for channel machining by SMEFC is explained in details. In order to verify the availability and universality of the proposed method, experimental verification has been conducted and the results showed a good matching with the simulation for electrolyte of NaCl. Using the similar method, two case studies of channel machining process by jet-ECM have been investigated as well.

2 Review of SMEFC system

Figure 1 shows the schematics and the solid model of the SMEFC system developed in the past work. The principle of electrolyte circulation is that the electrolyte droplet between the tool electrode and the workpiece is pushed up by the surrounding flowing air induced by a Venturi tube, whereby maintaining a fresh electrolyte supply and confining the electrolyte in the region of interest. The used electrolyte

containing the electrolysis products flows eventually into the electrolyte recycle tank through the channel in the suction head. A flexible membrane is placed on the top to seal the suction head and enhance the electrolyte recycling performance. The vacuum gap (VG) and inter-electrode gap (IEG) are also indicated in Figure 1.

Figure 1. Schematics of SMEFC and solid model

The workpiece is conveyed by a linear motorized stage (THORLABS MTS25-Z8) with the minimum achievable incremental movement of $0.05 \mu\text{m}$ and a bidirectional repeatability of $1.6 \mu\text{m}$. The travel range is 25 mm and the maximum velocity is 2.4 mm/s.

3 3D FEM simulation of channel machining by SMEFC

3.1 Problem statement of ECM simulation with moving electrode

Generally, an electrochemical machining process with a moving electrode can be modeled either by the analytical method [13], the boundary element method (BEM) [3] or the FEM [14, 15]. With regard to the electrolyte, ECM with moving electrode can be divided into two variants in general. In one situation it is treated as a free electrolyte, which means both the workpiece and the tool electrode are immersed in the electrolyte. In the other variant, it can be considered as a confined electrolyte, which means the electrolyte is confined in a small area on the workpiece, featuring an electrolyte / air interface. The conventional ECM milling and sinking ECM (Figure 2 (a) and (b)) fall into the first category. Jet-ECM and SMEFC (Figure 2 (c) and (d)) discussed in this research fall into the second category. The BEM approach has been utilized in the simulation of conventional ECM milling [3] and sinking ECM [16, 17]. Since only the electrode / electrolyte interface needs to be meshed in BEM instead of the whole electrolyte region, it is an ideal tool to model this situation, in which both the electrode and the workpiece are immersed in the well-stirred electrolyte. Nevertheless, it is hard to confine the electric field just in a moving volume, such as the electrolyte droplet in the SMEFC discussed in this research or the electrolyte column in jet-ECM. For the ECM with a confined electrolyte, simulation with a static electrode have been attempted by Hackert-Oschätzchen et al. [18, 19] for jet-ECM and by Guo et al. [10] for SMEFC. To the authors' knowledge, there is limited literature about

modelling the real-time workpiece shape evolution during the ECM process combining a confined electrolyte with a moving electrode, although actual channel machining experimental results have been reported by several research groups [7, 11, 19]. Recently, Liu et al. [20] has proposed a 3D FEM model to describe the jet-ECM of TB6 titanium alloy and clarified the dissolution mechanism. However, due to the complexity of the model, a real-time anode shape evolution was not achieved.

Therefore, this work aims at providing a feasible method to model a channel machining process with the confined electrolyte. As FEM provides better accuracy and numerical stability compared with other numerical calculation methods, a 3D FEM model of the channel machining by SMEFC has been developed on a commercial software platform (COMSOL 5.0) with the help of the moving mesh technique and a virtual electrolyte layer. The channel cross-sectional profile can be predicted by this model to a large extent. The proposed model can be also extended to jet-ECM after some modifications.

Figure 2. Schematics of (a) sinking/drilling ECM; (b) ECM milling; (c) jet-ECM; (d) SMEFC

3.2 Fundamental principle

The fundamental principle of the proposed 3D FEM simulation is shown in Figure 3. For simplicity, the schematic is in a 2D view, which describes how the channel forms through geometry deformation and node rearrangement. In Stage 1, the reaction scope and nodes are in the initial state. In Stage 2, the reaction scope moves, which can be understood as the confined electrolyte moving. In the same stage, the nodes on the left side are compressed and those on the right side are stretched. The reaction nodes always follow the reaction scope and the movement of the reaction node is also calculated in this stage. In Stage 3, geometry deforms according to the solution from Stage 2 and the nodes are rearranged again, which finishes one cycle. With this method, the reaction nodes can be moved and the geometry deformation is retained at the same time. In order to decrease the calculation errors, compressed nodes and stretched nodes should be enough to share the distortion induced by the geometry deformation. This principle will be implemented in the following section.

Figure 3. Schematic of the principle

3.3 Geometry establishment

There is a significant difference in the droplet shape between the moving state and the static state, as shown in the schematic (Figure 4). In the static mode, the shape of the electrolyte can be considered symmetric when all the conditions are well established (quasi-static conditions). However, in the scanning mode, the shape of the moving electrolyte droplet tends to be influenced by the channel shape generated by the electrochemical reactions, and consequently the shape of the electrolyte droplet is asymmetric perpendicular to the moving direction.

Figure 4. Static and moving electrolyte

Two assumptions are made for building up in the simulation:

- The first assumption is that there is a thin film of electrolyte with a predetermined average thickness

spreading on the workpiece. The aim of the virtual electrolyte film is to fulfill the requirements of mesh continuity during the mesh deformation induced by the electrochemical dissolution and electrolyte moving. The predetermined film thickness should be set to several microns, so there is still a large resistance between the electrode and the area covered with the virtual electrolyte film. Due to the small thickness of the virtual film, there is little current density and the corresponding metal dissolution is negligible. In addition, for the NaNO_3 electrolyte, the electrolyte passivation can hardly induce electrochemical dissolution on the stainless steel when the applied current density is lower than $20\text{A}/\text{cm}^2$, which also weakens the effects induced by this assumption.

- The second assumption is that the projection of the wetted area on the horizontal direction remains unchanged during the whole machining process. In reality, at the beginning of the process, there should be a change in the droplet shape and the size of the wetted area. When the depth reaches a stable value, the wetted area can be treated as a stable value. For the purpose of simplicity, the size of the wetted area in the initial phase is set to be the identical to the stable removal phase, since the stable removal phase is of interest. Figure 5 illustrates this assumption.

Figure 5. Schematics of the second assumption

Figure 6 depicts the geometry of the one-half 3D FEM simulation model. Only the electrolyte around the tip of the electrode was modelled to obtain a high calculation efficiency. It is worth mentioning that the function of the particularly long virtual film in the global view of Figure 6 is to average the mesh distortion induced by the moving mesh, since the mesh quality is of much importance for the calculation accuracy. This is an effective way to improve the calculation accuracy and efficiency when solving this model.

Figure 6. One-half 3D geometric model

Figure 7 illustrates the detailed dimensions of a generalized electrolyte droplet. Three contours are built up on separate planes with the space of d_1 and d_2 . Contour 1 is made up of two semi ellipses. One of them regards b_1 and t_1 as semi-major axis and semi-minor axis respectively. The other of them regards r_1 and t_1 as semi-major axis and semi-minor axis respectively. Contour 2 also follows the similar rule as shown in Figure 7. Contour 3 is a circle with the radius of the summation of the electrode outer radius (t) and the electrolyte thickness (h_1). The distance between the center of Counter 3 and that of Contour 1 and 2 is h_2 along the droplet moving direction. The external geometry of the electrolyte droplet is constructed by these 3 contours. The final geometry is derived by removing the geometry of the electrode tip.

Figure 7. Electrolyte droplet model in simulation

Some artificial relationships between the above-mentioned parameters are listed in Table 1. The virtual electrolyte layer should be as thin as possible to represent the actual situation. A thickness of 5 μm is finally selected as the thickness of the virtual electrolyte layer in the following simulation model.

Table 1. Geometrical parameters

Item	Dimension
r_2 (μm)	$\frac{3}{4} \times (r_1 - h_2 - t) + h_2 + t$
t_2 (μm)	$\frac{2}{3} \times (t_1 - t) + t$
b_2 (μm)	$\frac{1}{2} \times (b_1 + h_2 - t) - h_2 + t$
h_1 (μm)	20
h_2 (μm)	$0.25 \times t$
d_1 (μm)	45
d_2 (μm)	150

The dimensions mentioned above refer the actual geometrical shape of the moving droplet derived from the pictures of the actual moving droplet. For the geometrical parameters, Figure 8 shows 3 key dimensions (a_1 , a_2 and a_3) that construct the projection length of electrolyte droplet along the moving direction. Due to the limitations of the current monitoring system, it is impossible to measure a_3 , because it is below the top surface of the workpiece. Only a_1 and a_2 can be measured by the current monitoring system. Experiments

have been carried out to obtain fundamental information of a_1 , a_2 and the channel width.

Figure 8. Key dimensions of the electrolyte droplet

Two electrodes with different dimensions were utilized, and their geometrical parameters are listed in Table 2. Table 3 summarizes the common experimental conditions. Two kinds of electrolyte (NaCl and NaNO_3) and two workpiece materials have been tested. As indicated in ref. [11], the vacuum gap (VG) of $200\mu\text{m}$ guarantees the uniformity of the surface microstructures. Therefore, the VG is still set to be $200\mu\text{m}$. The inter-electrode gap (IEG) is set to be $50\mu\text{m}$. One of the workpiece materials is AISI420 (UDDEHOLM STAVAX® ESR) and the other is SS400 (supplier: MISUMI). Table 4 shows the specified experimental conditions for each group.

Table 2. Electrode dimensions

	Electrode 1	Electrode 2
Outer radius r (μm)	250	150
Inner radius t (μm)	90	60

Table 3. Common experimental conditions

Item	Description
IEG (μm)	50
VG (μm)	200
Anode potential (V)	8, 10
Electrolyte conductivity (S/m)	9.6
Feed rate (mm/s)	0.1, 0.2, 0.3

Table 4. Experimental groups

Group	Electrode No	Workpiece material	Electrolyte
A	1	SS400	NaCl

B	1	SS400	NaNO ₃
C	2	SS400	NaCl
D	2	AISI420	NaCl

The values for a_1 , a_2 and channel width have been recorded under the specified experimental conditions in Table 4. The results are summarized in Figure 9, which will be further used in Section 3.6. It can be noticed that a_1 is 1/2 ~ 3/4 of a_2 . With the increase of the feed rate, the machining area width also shows a decrease.

Figure 9. Statistics of a_1 , a_2 and channel width (a) Group A; (b) Group B; (c) Group C; (d) Group D

3.4 Domain and boundary settings

For the electrolyte domain, a primary current distribution is utilized, which means the current distribution only depends on the electrode and workpiece shape. Laplace's equation is followed.

$$\nabla \cdot (\sigma \nabla U) = 0 \quad (1)$$

where σ is the electrolyte conductivity during the machining, U the electric potential.

In order to take the bubbles into account, the Bruggeman's equation is used

$$\sigma = \sigma_0 (1 - \varepsilon)^{\frac{3}{2}} \quad (2)$$

where σ_0 is the conductivity without bubbles, ε the volume fraction of the bubbles.

It has been described that there is a dead water zone under the working electrode in SMEFC, which tends to accumulate bubbles [10]. Another fact is that the electrolyte in the machining region is blurred when observed with a camera at 30fps due to the fast bubble flowing. It is assumed that the volume fraction of the

bubbles is 45%.

To decrease the complexity in this initial work, the electrode kinetics is not considered to avoid nonlinear kinetic expressions, although a secondary current distribution has already been shown to be more suitable [21]. As a compensation, we use a fixed voltage drop over the electrolyte / electrode interface.

For the nitrate electrolyte, an overpotential is always considered in the ECM simulation. The overpotential is always measured under very small current density and different hydraulic conditions, which is quite different from the case of actual electrochemical dissolution under large current densities ($>30\text{A}/\text{cm}^2$). Rosenkranz et al. [22] have measured the voltage drop over the oxide layer on the anode surface instead. They found the voltage drop over the oxide layer is about 2.5V. Deconinck et al. [23] reported that the onset of reactions on the cathode and anode is -1.0V and 2.2V respectively. Since the concentration of the electrolyte and current density in this work is lower than that in the abovementioned two references, the fixed voltage drop at the anode surface (V_{da}) is assumed to be 1.5V.

In the active dissolution in the chloride electrolyte, a black solid layer is always found on the machined surface, which can be easily washed away. Therefore, it can be deduced that this layer is influenced by the hydraulic conditions. Haisch et al. [24] observed the similar black layer, which consists of iron oxides and inert metal carbides. That means there should be a voltage drop over this layer as well. Due to lack of the measurement of this black layer, the fixed voltage drop at the anode surface (V_{da}) is assumed to be 0.5V in this work. The voltage drop on the electrolyte / electrode interface is listed in Table 5.

Table 5. Assumption of voltage drop on the interfaces in simulation

Item	NaCl	NaNO ₃
Voltage drop on the electrode surface (V_{dc})	1 V	1 V
Voltage drop on the workpiece surface (V_{da})	0.5 V	1.5 V

According to the indications in Figure 10, the electric boundary conditions have been illustrated in Table 6.

Table 6. Boundary conditions of the FEM model

Boundary condition	Boundary	Property
Electric insulation	1, 3~7, 11, 12	$\mathbf{n} \times \mathbf{J} = 0$
Electric potential	2	$V_{\text{anode}} - V_{da}$
Electric potential	8~10	V_{dc}

Table 7 summarizes the boundary conditions for the whole geometry deformation, where v_x , v_y and v_z denote the mesh velocity along x , y and z direction, d_x and d_z mesh displacement along x and z direction respectively, v_s the feed rate of the electrolyte droplet, v_a the normal mesh velocity of Boundary 2.

Table 7. Boundary conditions of the FEM model

Boundary condition	Boundary	Property
Prescribed mesh displacement	3,4	$d_x = 0, d_z = 0$
Prescribed mesh displacement	1,5,6	$d_x = 0$
Prescribed normal mesh velocity	2	v_a
Prescribed mesh velocity	8~12	$v_x = 0, v_y = 0, v_z = v_s$
Prescribed mesh velocity	7	$v_x = 0, v_z = v_s$

Figure 10. Indication of boundaries

The deformation of the electrolyte domain is partially defined by its boundaries. The mesh deformation is computed by Laplace smoothing approach, which solves the partial differential equation:

$$\frac{\partial^2 x}{\partial X^2} + \frac{\partial^2 y}{\partial Y^2} + \frac{\partial^2 z}{\partial Z^2} = 0 \quad (3)$$

where (x, y, z) are the coordinates of the deformed positions, (X, Y, Z) the coordinates of the original positions.

Based on these prescribed conditions, Boundary 7 can be attached to boundary 2, whereby maintaining the thickness of the pre-defined thin electrolyte layer almost unchanged.

3.5 Charge number and current efficiency

The normal mesh velocity v_a on Boundary 2 was calculated according to the electrochemical properties of workpiece material. In this simulation, the current efficiency was also considered due to its significant influence. V.M. Volgin et al. [25] evaluate the effects of current efficiency on electrochemical micromachining by moving electrode. Their results show that the shape and sizes of machined surface are highly dependent on the current efficiency. In this work, the current efficiency for NaNO_3 electrolyte follows the results of ref. [26]:

$$i_{Me^{z+}} = \varphi(i) \times i \quad (4)$$

where $\varphi(i)$ is the current efficiency, which is a function of local current density i , $i_{Me^{z+}}$ the current density for

metal dissolution.

The dissolution rate at the anode surface is proportional to the current density $i_{Me^{z+}}$. According to the Faraday's law, the relation between v_a and $i_{Me^{z+}}$ is:

$$v_a = -\frac{M \times i_{Me^{z+}}}{z(i) \times F \times \rho} = -\frac{M \times \varphi(i) \times i}{z(i) \times F \times \rho} \quad (5)$$

where v_a is the anode removal velocity, M the molar mass, $z(i)$ the charge number and ρ the density of the anode material.

According to equation (5), the charge number $z(i)$ should be determined based on the elements of the workpiece material. Since iron content in SS400 is over 99%, the charge number is only accounted for iron. Table 8 shows the elements of the workpiece material AISI 420.

For NaCl electrolyte, the chloride in the electrolyte can get through the oxide layer on the anode, which make the dissolution happens at a lower valence state (Table 8) [27]. The electrochemical dissolution occurs even at low current densities (<1 A/cm²). The current efficiency is considered as 100%, although Haisch et al.[24] has reported that sometimes the current efficiency is larger than 100% due to the non-electrochemical dissolution.

Table 8. Material composition of AISI420

Element	Mass fraction (%)	Charge number (NaCl)	Charge number (NaNO3)	Molar mass
C	0.38	4	4	12
Si	0.9	4	4	28
Mn	0.5	2	2	55
Cr	13.6	3	6	52
V	0.3	5	5	51
Fe	Balance (84.32)	2	$(3x+2)/(x+1)$ $(Fe^{3+}:Fe^{2+}=x:1)$	56
Average		2.1706		55.01

For the NaNO₃ electrolyte, the charge number of iron and current efficiency are more controversial. In ref. [22], the experiment shows that $Fe^{2+}:Fe^{3+}=1:2$ and the average of the charge number of Fe is 2.67. Lohrengel et al. [26] found that the charge number of Fe (i.e., the proportion of Fe^{2+} and Fe^{3+}) also changes with current density increasing. The proportion of Fe^{2+} and Fe^{3+} were obtained through measuring the plot in Figure 4 of ref. [26], as shown in Table 9. Other values are calculated by linear interpolation.

Table 9. Current efficiency and charge number derived from Figure in ref. [26]

Current density (A/cm ²)	Fe ³⁺ (%)	Fe ²⁺ (%)	Fe ³⁺ :Fe ²⁺	Oxygen (%)	Current efficiency $\varphi(i)$	Charge number $z(i)$
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≤ 7	0	0	∞	100	0	3
11	8.11	1.35	6.00	90.54	0.0946	2.8571
21	39.19	10.00	3.92	50.81	0.4919	2.7967
25	56.76	16.22	3.50	27.02	0.7298	2.7778
29	60.27	21.62	2.79	18.11	0.8189	2.7361
34	66.49	24.32	2.73	9.19	0.9081	2.7319
39	71.62	27.03	2.65	1.35	0.9865	2.7260
52	64.86	32.43	2.00	2.71	0.9729	2.6667
67	64.86	35.14	1.85	0	1.0000	2.6491
≥ 75	65.14	34.59	1.88	0.27	0.9973	2.6528

The trends of current efficiency and charge number are demonstrated in Figure 11. Above 40 A/cm², the current efficiency is almost 100%. The charge number experienced a decrease from 3 to 2.6528. The simulation process will take the current efficiency and the charge number into account, both of which vary with the current density.

Figure 11. Current efficiency and charge number changing

3.6 Simulation results and experimental verification

After these preparations, 8 simulations have been conducted and compared with corresponding experimental results in terms of the channel cross-sectional profiles. The detailed conditions for every group are listed in Table 10, in which geometrical parameters t_l , b_l and r_l are obtained from Figure 9 to construct the geometry model. Electrolyte species, workpiece materials, electrode dimensions, feed rates and machining voltages are evaluated by simulation and experiments.

Table 10. Experiment and simulation conditions

Condition No.	Electrode No.	Workpiece	Electrolyte	Feed rate (mm/s)	Voltage (V)	t_l (μ m)	b_l (μ m)	r_l (μ m)
# 1	1	SS400	NaCl	0.2	10	367.65	417.9	383.3

# 2	1	SS400	NaNO ₃	0.2	10	427.25	423.3	372.9
# 3	2	SS400	NaCl	0.2	10	285.45	387.7	305.9
# 4	1	SS400	NaCl	0.1	10	378.65	440.3	366.5
# 5	1	SS400	NaCl	0.3	10	363.85	410.7	391.3
# 6	1	SS400	NaCl	0.2	8	345.55	389.1	398.9
# 7	2	AISI420	NaCl	0.2	10	276.95	386.1	302.7
# 8	1	SS400	NaNO ₃	0.2	8	401.00	413.3	381.9

3.6.1 Analysis of evolutionary process

Figure 12 and Figure 13 illustrates the whole mesh, mesh on Boundary 2 and current density distribution on Boundary 2 at 4 time points (0s, 2s 4s and 5.8s) under Condition 1 and Condition 3 in Table 10 respectively.

Three phases can be distinguished:

- Initial phase: The electrolyte droplet is static and the deformation does not happen.
- Stable phase: The electrolyte droplet moves stably with a uniform material removal rate.
- Transitional phase: The duration between the initial phase and the stable phase.

During the transitional phase, the electrolyte / workpiece interface evolves from a horizontal state to an inclined condition due to the combined effect of material removal and the electrolyte droplet moving. After this phase, the electrolyte droplet moves forward and removes the workpiece material in a stable way, maintaining the inclination of the electrolyte / workpiece interface unchanged until the end, which is similar with the concept of “local impact angle” mentioned in [28]. From the mesh on Boundary 2, compressed and stretched mesh gradually varies with the formation of the channel, which follows the principle introduced in Section 3.2. Figure 14 shows the profile evolution and current density distribution of the central edge of Boundary 2 from 0s to 5.8 s under Condition 1, in which a flat bottom surface can be derived finally along the moving direction of the electrolyte droplet. The double peaks of current density change from near equal magnitude to unequal magnitude due to the geometry deformation.

Figure 12. The whole mesh at (a) 0 s, (d) 2 s, (g) 4 s, (j) 5.8 s; Mesh of Boundary 2 at (b) 0 s, (e) 2 s, (h) 4 s, (k) 5.8 s; Current density distribution on Boundary 2 at (c) 0 s, (f) 2 s, (i) 4 s, (l) 5.8 s under Condition 1

Figure 13. The whole mesh at (a) 0 s, (d) 2 s, (g) 4 s, (j) 5.8 s; Mesh of Boundary 2 at (b) 0 s, (e) 2 s, (h) 4 s, (k) 5.8 s; Current density distribution on Boundary 2 at (c) 0 s, (f) 2 s, (i) 4 s, (l) 5.8 s under Condition 3

Figure 14. Channel profile and current density along the moving direction under Condition 1

3.6.2 Effects of electrolyte species

Figure 15 shows the experimental channel cross-sectional profiles generated under NaCl (Condition 1) and NaNO₃ (Condition 2) respectively. For the convenience of labeling, “Sim α ”, “Exp α ” and “Err α ” are utilized to indicate the simulation curve, the experiment curve and the corresponding error curve under Condition α . The experimental cross-sectional profiles were measured by Mitutoyo CS3200 profiler. The stylus radius is 3.3 μm . For NaCl, two peaks with the height of around 10 μm in the error curve can be observed, which always appear in the following part. One possible reason is the uneven electrolyte conductivity during the machining process due to the influence of bubbles and heat. More errors exist in the case of NaNO₃. It can be found that there are three peaks with the height of around 13 μm in the error curve, as shown in Figure 15 (b). The current simulation model cannot achieve this experimental curve pattern for NaNO₃.

Figure 15. Simulation and experiment (a) profiles and (b) errors in NaCl (Condition 1) and NaNO₃ (Condition 2)

Figure 16 illustrates a possible explanation for this deviation, in which two profiles derived from NaNO₃ (Condition 2 and 8) are shown. For both of the profiles, excessive removal can be observed. In past work

[10], static situation has been simulated and the results indicated that a dead water zone forms under the electrode surface and near the edge of the meniscus. When the electrode move slowly, it is assumed that similar hydraulic conditions occur. The vortex forms near the edge of the electrolyte droplet, which accumulates reaction heat and Joule heat, resulting in an increase in the temperature. Since the temperature will enhance the electrolyte conductivity it will also further increase the local current density. As a result, more materials is removed. A puzzling fact is that this kind of excessive removal does not exist or is not so obvious when it comes to the NaCl electrolyte. In Figure 15, the profile derived from NaCl electrolyte is rougher than that derived from NaNO₃ electrolyte due to pit corrosion. This can be confirmed by the morphologies of the channels in Figure 17, which were measured by a 3D profiler (SENSOFAR S Lynx) using the interferometry mode. From the point of fluid mechanics, the roughness plays an important role in the whole flow domain, which is possible to induce translation, affect the boundary layer and change the pressure gradient. Another possible reason is the difference in the viscosity (1.11 mPa • s for NaNO₃ and 1.13 mPa • s for NaCl at 20°C), which can influence the vortex formation. The temperature in the machining region also influences the viscosity. Since there is no enough evidence yet to explain the profile generated in NaNO₃ electrolyte, only cases in NaCl electrolyte are compared.

Figure 16. Schematic of the removal process in NaNO₃ electrolyte

Figure 17. Topography of the channel (a) NaCl (Condition 1) (b) NaNO₃ (Condition2)

3.6.3 Effects of workpiece material

The cross-sectional profiles obtained on different workpiece materials are demonstrated in Figure 18 (a). The channel morphology of AISI420 is smoother than that of SS400, as shown in Figure 19. Due to the approximative electrochemical equivalent of SS400 and AISI420, the experimental curves are very close. The maximum error is around 8 μm for SS400 and 6 μm for AISI420, as shown in Figure 18 (b).

Figure 18. Simulation and experiment (a) profiles and (b) errors on SS400 (Condition 3) and AISI420 (Condition 7)

Figure 19. Topography of the channel (a) SS400 (Condition 3) (b) AISI420 (Condition 7)

3.6.4 Effects of electrode dimension

The electrode dimension has significant influence on the cross-sectional profiles, as shown in Figure 20. The larger electrode tends to widen and deepen the channel when other conditions maintain the same. The simulation profile can reflect this point as well. The maximum error is around 25% (Figure 20 (b)). The simulation model fit the case with the smaller electrode better according to the errors.

Figure 20. Simulation and experiment (a) profiles and (b) errors with the electrode with the outer diameter of 500 μm (Condition 1) and 300 μm (Condition 3)

3.6.5 Effects of feed rate

The effects of feed rates are evaluated in Figure 21. With the increase of the feed rate, the maximum channel depth increases from 30 μm to 80 μm (Figure 21 (a)). The maximum error for 0.2 mm/s and 0.3 mm/s is

around 10 μm . The maximum error for 0.1 mm/s is around 17 μm . One possible reason for the larger error is that the geometry in the simulation has larger deviations from the actual situation with the machining depth growing.

Figure 21. Simulation and experiment (a) profiles and (b) errors under feed rates of 0.1mm/s (Condition 4), 0.2mm/s (Condition 1) and 0.3mm/s (Condition 5)

3.6.6 Effects of voltage

The applied voltage is also investigated. As demonstrated in Figure 22, a higher machining voltage leads to a wider and deeper channel profile, in the experiment as well as in the simulation. In Figure 22(b), the maximum error for 10V is bigger than that for 8V, which may be also attributed to the deviations in the simulation geometry.

Figure 22. Simulation and experiment (a) profiles and (b) errors under voltages of 8V (Condition 6) and 10V (Condition 1)

4 3D FEM simulation of channel machining by jet-ECM

A schematic of jet-ECM is demonstrated in Figure 23. Different from the simulation of SMEFC, the

assumption of the virtual thin electrolyte film is not required, since the thin electrolyte film really exists within the hydraulic jump in the actual jet-ECM process as shown in Figure 23. As in jet-ECM, the flow rate is always tens of meters per second, so the effects of bubbles can be neglected. The specific dimensions R , L , t_e , h_e and IEG in Figure 23 are utilized to approximately construct the electrolyte geometry. In reality, the transition region between the electrolyte column and the electrolyte layer should be a curve. However, because there is no definite rule to determine the curve, a straight line is utilized instead in this part.

Figure 23. Schematic of jet-ECM

4.1 Case study 1

The first case study of jet-ECM is in micro scale. The geometrical parameters and machining conditions refer to the work of ref. [6]. The geometry parameters in the simulation are listed in Table 11.

Table 11. Parameters for the electrolyte region

Item	Value
R (μm)	65
L (μm)	200
t_e (μm)	10
h_e (μm)	27.5
IEG (μm)	300

The geometry model and boundaries are illustrated in Figure 24 and boundary settings are listed in Table 12. These settings are similar with the settings of SMEFC. Considering that the IEG is quite large compared to the jet diameter, 0V is applied to the top surface of the electrolyte column (Boundary 10), instead of modeling the inner surface of the nozzle.

Figure 24. Indication of boundaries

Table 12. Boundary conditions

Boundary condition	Boundary	Property
Prescribed mesh displacement	3,4	$d_x = 0, d_z = 0$
Prescribed mesh displacement	1,5,6	$d_x = 0$
Prescribed normal mesh velocity	2	v_a
Prescribed mesh velocity	10	$v_x = 0, v_y = 0, v_z = v_s$
Prescribed mesh velocity	7,8,9	$v_x = 0, v_z = v_s$

The simulation conditions are summarized in Table 13.

Table 13. Simulation conditions

Item	Description
Mode	Constant voltage
Anode potential (V)	102.5
Electrolyte conductivity (S/m)	14
Electrolyte	NaNO ₃
Workpiece	Stainless steel (AISI420)
Machining time (s)	3
Feed rate v_s (mm/s)	0.5

The simulation results are illustrated in Figure 25, in which the initial phase (0s), transitional phase (0.5s) and the stable phase (1.5s) are presented. The maximum current density at the initial phase is 370 A/cm². While, it decrease to 327 A/cm² at the stable phase due to the increase of the resistance. The simulation cross-sectional profile is shown in Figure 26, with a maximum depth of 25μm.

Figure 25. Potential distribution at (a) 0s (b) 0.5s (c) 1.5s Current density distribution on the workpiece surface at (d) 0s (e) 0.5s (f) 1.5s

Figure 26. Cross-sectional profile from simulation

4.2 Case study 2

The second case study is a mesoscale jet-ECM. Mitchell-Smith et al. [29] recently proposed a novel method to modulate the energy distribution through redesign of the nozzle-tips in jet-ECM. In that work, a simplified 2D stochastic model has been developed to evaluate the performance of the nozzles-tips in terms of the channel cross-sectional profiles on Inconel 718. Using the proposed 3D FEM model in this paper, it is possible to directly simulate the final channel profile based on the Faraday's law, enabling another way to evaluate the nozzle-tip design. As a demonstration, three nozzle-tips proposed in that work are compared in this part. They are standard nozzle, center point element (CPE) and symmetrical twin element (STE), the geometries of which are shown in Figure 27 (a), (b) and (c) respectively. According to the machining conditions mentioned in that work, the constant current of 900 mA for 1 mm nozzle is applied. The initial machining gap is set to 150 μm , which is derived by measuring the plot in Figure 14 of ref. [29]. According to ref. [30], for Inconel 718, the density is 8.228g/cm^3 , the average atomic weight 59.79g/mol and the average valencies 3.0 ± 0.2 . Since the value of t_e , h_e , and L are not presented in their work, hypothetical

values are used. Table 14 and Table 15 summarized the geometrical parameters and the machining conditions respectively.

Table 14. Parameters for the electrolyte region

Item	Value
R (μm)	500
L (μm)	1250
t_e (μm)	50
h_e (μm)	140
IEG (μm)	150

Table 15. Simulation conditions

Item	Description
Mode	Constant current
Machining current (mA)	900
Electrolyte conductivity (S/m)	12.2 [31]
Electrolyte	NaNO_3
Feed rate (mm/s)	0.5

Because the IEG is much smaller than the nozzle diameter, the voltage of 0V needs to be set to the nozzle inner surface instead of the simplification in Case 1. The potential and current density distribution during the stable phase have been given in Figure 27. The different configurations of the cathode area and location result in the difference in the potential distribution as shown in Figure 27 (d), (e) and (f). The maximum current density for CPE occurs on the central line (Figure 27 (h)). However, the maximum current density for STE occurs near the channel edge. The current density distribution for the standard nozzle-tip is more average. The difference in current density finally contributes to the different cross-sectional profile.

Figure 27. Geometry of (a) standard tip (b) CPE tip (c) STE tip Potential distribution for (d) standard tip (e) CPE tip (f) STE tip Current density distribution for (g) standard tip (h) CPE tip (i) STE tip

The simulated profiles for these three nozzle-tips are shown in Figure 29, together with the experimental profiles and the predicted profiles in the original work. It can be found that the simulated profiles has higher machining localization, which means more materials are removed in the central area and less near the edge. The ignorance of current efficiency (CE) and secondary dissolution (SD) may lead to this phenomena. To verify this assumption, the current efficiency is taken into account, which refers to Figure 2 of ref. [32]. The values are listed in Table 16 and other values are calculated by linear interpolation. The secondary dissolution means that part of the bottom surface of the electrode also works in addition to the inner surface because of the reflected electrolyte. Liu et al. [33] has concluded that too small IEG or too large flow rate tended to induce secondary dissolution. A ring on the bottom surface with a width of 50 μm near the inner surface is regarded as the additional working surface. A simulation considering only SD and another including both SD and CE together have been carried out respectively. The resulted profiles can be found in

Figure 29. For STE and CPE, the situation considering SD and CE fit the experimental curves better. For the standard nozzle, there is still a maximum deviation of 10 μm from the experimental curve in the central part.

Table 16. Current efficiency of Inconel 718 in NaNO_3 solution [32]

Current density (A/cm^2)	Current efficiency
≤ 3.62	0.845
6.64	0.757
11.17	0.715
15.09	0.692
18.72	0.683
22.34	0.674
26.26	0.669
29.89	0.665
≥ 33.81	0.660

Figure 28. Simulation of potential with secondary dissolution (a) standard (b) CPE (c) STE

Figure 29. Simulation result of cross-sectional profiles (a) standard (b) CPE (c) STE

These two study cases show that the proposed 3D FEM model has the simulation applicability in the virtual jet-ECM, which offers a potential for the design of the nozzle-tips. If accurate electrolyte geometries can be obtained during the stable phase, it is also possible to reach more accuracy in the simulated profiles by this method.

5 Conclusion

1. A 3D FEM simulation model for the channel machining by SMEFC and jet-ECM is proposed in this work. The key to the proposed 3D FEM simulation model is the introduction of the virtual thin electrolyte film and the moving mesh technique, which enables the electrolyte droplet moving on the workpiece in a relatively large range. The model can synchronously present the distribution of current density and potential together with the workpiece profile change, which enhance the understanding of this kind of ECM process. This proposed model is capable of predicting the channel cross-sectional profile, decreasing the trial and error experiments. The electrolyte species, workpiece, electrode dimension, feed rate, machining voltage are evaluated in terms of the cross-sectional profiles. The errors may come from the uneven electric conductivity and the modeling deviation.
2. The proposed simulation method has been extended to simulation of channel machining by jet-ECM. It offers a more intuitive way to investigate jet-ECM process since there are still few FEM models capable of describing the jet-ECM process in a scanning way. The two case studies of micro scale and mesoscale jet-ECM have been demonstrated in this research, showing a possibility in modelling of grooving process by jet-ECM. In addition, the influence of the current efficiency and secondary dissolution on the simulation is also revealed.
3. This simulation method is still at its developmental stage. Figure 30 demonstrates a possible workflow of the proposed simulation model for the confined electrolyte based ECM method in the future. Ideally, there should be a geometric model generator for simulation, which can generate suitable model according to the given machining conditions based on the mass geometric measurement data and its internal algorithms. However, how to accurately obtain the 3D spatial geometry of the confined electrolyte with the camera or other sensors is still a problem. Another improvement of this model will be the addition of flow field and heat transfer calculation, aiming to simulate the channel cross-sectional profiles generated under the NaNO_3 electrolyte.

Figure 30. A possible workflow

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