Two Phase Simulation of Electrochemical Machining

Garg Mayank*, Masanori Kunieda*
(Received on January 27, 2017)

*Department of Precision Engineering, The University of Tokyo, Tokyo, Japan

Abstract

The machining accuracy of Electrochemical Machining (ECM) is affected by the temperature and bubbles. The effect of bubbles in the simulation can be considered by first calculating the volume fraction of gas distribution (using bubbly flow approximation in this study) and then approximating the effective conductivity in the inter-electrode gap by using Bruggemann equation. Since, Bruggemann equation is independent of bubble diameter and distribution, its dependency on that was investigated in this study. Moreover, the effect of the bubbles generated on the machining accuracy of the axi-symmetric work piece with different flow rates was also investigated.

Keywords: Bruggemann equation, bubbly flow, inter-electrode gap

1. INTRODUCTION

The design consideration in electrochemical machining is very difficult. There are many factors that affect the speed and accuracy of the machining like generation of bubbles, flow rate, electrolyte temperature rise in the gap, etc. so that prediction of the tool geometry to machine a required shape and simulating the work piece removal by a given tool remains a challenge even today.

The effects of the bubbles and temperature in the simulation models have been considered by many researchers in the past. Deconinck et al.1) solved for electrical, electrolyte flow model and thermal model to simulate the machining process. They considered the fluid to be single phase electrolyte. Klocke et al.2) considered the flow in the inter-electrode gap to be two phase by using bubbly flow model and simulated the final electrochemically machined profile of engine blade using COMSOL Multiphysics software. To include the effect of bubbles, they calculated the volume fraction within the electrolyte using the bubbly flow approximation and then corrected the electrical conductivity by using Bruggemann equation3). However, Bruggemann equation that was used to correct the electrical conductivity has no terms related to bubble diameter and distribution of bubbles in it. Its dependency on them within the inter-electrode gap needs to be investigated.

Shimasaki et al.4) found that in electrochemical machining, the electrolyte can also boil in the inter-electrode gap by Joule heating and bubbles can cover most of the area within. Thus, the validity of the Bruggemann equation with respect to the volume fraction also needs to be studied more.

So, this study is based on (i) determination of dependency of Bruggemann equation on bubble diameter, distribution of bubbles and the volume fraction, and, (ii) The effect of the bubbles generated on the machining accuracy of the axi-symmetric work piece with different flow rates.

2. BRUGGEMANN EQUATION

To approximate the macroscopic properties such as electrical conductivity, permittivity etc. of the materials like composites, porous materials etc., many theories have been presented in the past. The brief explanation of some of them is as follows:

For infinitely dilute composites or suspension of filler particles, the Maxwell expression5,6) for electrical conductivity can be generalized to:

\[ \frac{\sigma}{\sigma_m} = 1 + 3 \left( \frac{\sigma_d - \sigma_m}{\sigma_d + 2\sigma_m} \right) \phi \] (1)

Where, \( \sigma \) is the electrical conductivity of the composite (or averaged conductivity), \( \sigma_d \) and \( \sigma_m \) are the electrical conductivities of the filler (dispersed phase) and matrix (dispersion medium), respectively, and \( \phi \) is the volume fraction of the filler.

Eq.1 cannot be applied to relatively high concentration of particles as the interaction between the particles was not considered in its derivation. To extend the applicability of this equation to concentrated systems, a differential effective medium approach was used.

According to this approach, a concentrated composite is considered to be obtained from an initial matrix phase by successively adding infinitesimally small quantities of particles to the system until the final volume fraction of filler is reached. The incremental change in electrical conductivity upon the addition of an infinitesimally small quantity of particles to the system can be determined from the generalized Maxwell equation. Therefore,

\[ d\sigma = 3\sigma \left( \frac{\sigma_d - \sigma}{\sigma_d + 2\sigma} \right) d\phi \] (2)
The Eq.2 can be rewritten as:

\[
\frac{1}{3} \left( \frac{1}{\sigma} + \frac{3}{\sigma_d - \sigma} \right) \, d\sigma = d\varphi
\]  

Moreover, since Eq.1 is valid for infinitely dilute composites, it is assumed that total volume is constant and any new addition of filler would not affect the total volume significantly. However, if the composite is not dilute i.e. concentrated, then the total volume will increase as the filler is added. This means that when a differential quantity of new particles are added to the existing composite, the increase in the actual volume fraction of the dispersed phase is larger than \( d\varphi \). The increase in the volume fraction of the dispersed phase is \( d\varphi/(1 - \varphi) \). Thus, Eq.3 can be modified as:

\[
\frac{1}{3} \left( \frac{1}{\sigma} + \frac{3}{\sigma_d - \sigma} \right) \, d\sigma = \frac{d\varphi}{1 - \varphi}
\]  

Integrating the above equations with the limit \( \sigma \rightarrow \sigma_m \) at \( \varphi \rightarrow 0 \), we get

\[
\left( \frac{\sigma}{\sigma_m} \right)^\frac{1}{3} \left( \frac{\sigma_d - \sigma_m}{\sigma_d - \sigma} \right) = \frac{1}{1 - \varphi}
\]  

In electrochemical machining, the dispersed phase is bubble, thus \( \sigma_d = 0 \). Thus Eq.5 reduces to:

\[
\sigma = \sigma_m (1 - \varphi)^\frac{2}{3}
\]  

which is so called Bruggemann equation and is widely used to approximate the electrical conductivity within the inter-electrode gap.

One major drawback of the Bruggemann equation is that they fail to predict the right behavior when \( \varphi \rightarrow \varphi_m \), where \( m \) is the maximum packing volume fraction of particles where the particles touch each other. For random close packing of uniform spheres, \( \varphi_m \) is 0.637. In electrochemical machining, this may be the case when most of the gap is occupied with the bubbles.

To consider the above explained effect, Pal\(^6\) introduced another term \( k_0 = 1/\varphi_m \) to account for the so-called ‘crowding effect’ caused by packing difficulties of particles or bubbles as shown in Eq.7 as follows:

\[
\frac{1}{3} \left( \frac{1}{\sigma} + \frac{3}{\sigma_d - \sigma} \right) \, d\sigma = \frac{d\varphi}{1 - k_0 \varphi}
\]  

After integrating the above equation and substituting \( \sigma_d = 0 \), the equation reduces to:

\[
\sigma = \sigma_m \left( 1 - \frac{\varphi}{\varphi_m} \right)^\frac{2}{3}
\]  

It can be noted that Bruggemann equation is the special case of the above equation when \( \varphi_m = 1 \). The author of the above paper also did experiments in which he found that both Eq.6 and Eq.8 predicted nearly the same average electrical conductivity for smaller \( \varphi \) (\( \varphi < 0.2 \)). However, when volume fraction was increased further, Eq.8 approximated better than the Eq.6.

Thus we can note that Eq.8 can be used in electrochemical machining simulation instead of Bruggemann equation. However, in the above analysis effect of coalescence or breaking of bubbles, resulting in diameter and distribution change, was neglected.

3. EFFECT OF DISTRIBUTION AND DIAMETER OF BUBBLES ON BRUGGEMANN EQUATION

In ECM, when NaCl solution is used, most of the bubbles are Hydrogen and concentrated towards cathode. However, when NaNO\(_3\) is used, O\(_2\) bubbles are also evolved significantly from the anode. Thus, to check for the effect of distribution of bubbles, whether the bubbles are concentrated towards anode, cathode or in the middle, simulation was performed. Moreover, the effect of diameter of bubbles was also investigated.

To check for the effect of bubble diameter, a cube of volume 100x100x100 \( \mu \)m\(^3\) was considered whose electrical conductivity was 5 S/m without any bubble. Considering the same volume fraction 0.18, bubbles (of electrical conductivity 0 S/m) of different radii (thus different no. of bubbles) were distributed randomly within the cube and voltage was applied as shown in Fig.1. Then, the average electrical conductivity was calculated as shown in Fig.2 by calculating the electric field distribution and current density.

![Fig. 1 Random distribution of different radii bubbles considering same volume fraction 0.18](image)

![Fig. 2 Effect of bubble diameter on the average conductivity calculated](image)

From Fig.2, It can be noted that the average conductivity calculated considering different radii of bubbles is almost equal to that obtained by Bruggemann equation. Thus, we can conclude that the coalescence of
bubbles have no effect on the calculated average electrical conductivity.

To check for the effect of distribution of the bubbles, in the same volume of cube, with the same volume fraction of 0.10 and same radius, bubbles were distributed according to four distributions as shown in Fig. 3.

![Fig. 3 Different distribution of bubbles considering same volume fraction and radius](image)

Based on the previous assumptions, the momentum and continuity equations can be combined for the two phases and can be written as Eq. 9 as follows:

$$\frac{\partial (\varnothing \rho_l \varnothing \rho_g \varnothing \rho_l)}{\partial t} + \varnothing \cdot (\varnothing \rho_l \varnothing \rho_l \varnothing + \varnothing \rho_g \varnothing \overline{u}_g) = 0$$

where, \(u_t\) is the velocity vector of the liquid phase, \(\varnothing_l\) is the phase volume fraction of liquid, \(F\) is any additional volume force (which is zero here), \(\mu_l\) is the dynamic viscosity of the liquid, \(\mu_T\) is the turbulent viscosity and \(P\) is the pressure.

The continuity equation can be written as Eq.10:

$$\frac{\partial (\varnothing \rho_l \varnothing \rho_g \varnothing \rho_l)}{\partial t} + \varnothing \cdot (\varnothing \rho_l \varnothing \rho_l \varnothing + \varnothing \rho_g \varnothing \overline{u}_g) = 0$$

The gas velocity is the sum of liquid velocity, slip velocity (between gas and bubble) and drift velocity \(^8\). The slip velocity is calculated by considering a balance between the viscous drag and the pressure gradient which is given as:

$$\frac{\partial (\varnothing \rho_g \varnothing \overline{u}_g)}{\partial t} + \varnothing \cdot (\varnothing \rho_g \varnothing \overline{u}_g) = 0$$

4. **BUBBLY FLOW**

To consider the effect of gas in the electrolyte, a two phase model is necessary, which is considered by Bubbly flow \(^8\). Bubbly flow is a simplification of the microscopic model for two-phase fluid flow which relies on the following assumptions:

- The liquid density is significantly large in comparison to gas density,
- The velocity of the gas bubbles relative to the liquid is determined by a balance between viscous drag and pressure forces (please see Eq.12),
- The two phases share the same pressure field, and
- The effect of coalescence is not considered.

![Fig. 4 Effect of distribution of bubbles on the average conductivity calculated](image)

The average conductivity calculated is shown in Fig. 4. It shows that the distribution of bubbles has effect on the average calculated conductivity, thus affects the average current density calculations. However, the effect of distribution is less than 5% in the above simulation, so if the precision is acceptable in 5% range, then the effect of distribution can be ignored.

In the present simulation, that will be explained in the next section, since the low voltage conditions were used, Bruggemann equation was used ignoring the effects of distribution to approximate the electrical conductivity.

5. **MODEL AND SIMULATION METHOD**

5.1 **Experimental Model**

Fig. 5 shows the schematic diagram of the experimental model. The steel plate cathode was fed towards the carbon steel (S45C) axi-symmetric workpiece under the conditions as shown in Table 1.

Since, the S45C rod surface and steel plate needs to be perfectly parallel in order to maintain uniform inter electrode gap before machining to finally measure the contour difference before and after machining, the rod was ground initially and the angle between the plate and rod was adjusted initially to make both the electrodes parallel to each other.
5.2 Simulation Model
Corresponding to Section A shown in Fig. 5, a simulation model was developed and is shown in Fig. 6. The effects of overpotential and the voltage drop inside the electrodes were neglected while choosing this type of model.

5.3 Explanation About Simulation
The flow chart, as shown in Fig. 7, explains the simulation where

\[
\overline{V_n} = \frac{M \bar{J}}{\rho z F} \text{ [m/s]} \quad (14)
\]

Here, \(\overline{V_n}\) is the material removal velocity, \(M\) is the molar mass, \(\bar{J}\) is the current density, \(z\) is the electrochemical valence of the material of the work piece, \(F\) is Faraday's constant and \(\rho\) is the density of the material, and

\[
N_g = \frac{JRT}{zFP} \text{ [Kg/(m²s)]} \quad (15)
\]

where, \(N_g\) is the amount of \(H_2\) gas evolved, \(J\) is the absolute value of current density, \(T\) is temperature, \(R\) is gas constant and \(P\) is the local pressure.

In this simulation, the effects of temperature were ignored as we wanted to compare the effect of bubbles only with different flow rates. The simulation was performed using COMSOL Multiphysics software which is a Finite Element Method (FEM) based software.

6. SIMULATION RESULTS
6.1 Volume Fraction Of Gas
Fig. 8 shows the results of volume fraction of hydrogen gas in the electrolyte at two different inlet pressures of 0.04 MPa and 0.05 MPa. As expected, the volume fraction distribution is higher in case of lower inlet pressure.

![Fig. 8 Volume fraction of hydrogen gas](image)
6.2 Comparison Between Simulated And Machined Work Piece Profiles

On the final work piece profile, we marked 4 points A, P, B, Q (as shown in Fig. 8). At points A and B, much more material was removed because of high current density. So, to measure experimentally, we chose points P and Q from where profile was varying smoothly.

Fig. 9 shows the simulated and machined work piece profiles and the corresponding inter-electrode gap obtained. It was shown that the material removal at outermost point Q was less than the innermost point P. However, this difference was reduced at high inlet pressure, which was verified by the simulations. At higher pressure, the difference between final inter-electrode gap between simulations and experiments was less than the case of lower inlet pressure. The difference can be due to not considering the temperature, limitation of approximation by Bruggemann equation as the distribution of bubbles can affect the electric field distribution as it is not considered in the equation etc.

7. CONCLUSIONS

(a) The distribution of bubbles affect the approximation of electrical conductivity by Bruggemann equation. However, it should be noted that it can be used without a significant error in the practical ECM gap where volume fraction of gas is less than 0.2.
(b) The effect of bubbles in the simulation was considered by using bubbly flow model. In simulation it was found that there is less material removal at the outermost point than the innermost point in the axisymmetric tool with radial flushing flow, which was validated by the experiments.
(c) The final material removal profile was simulated in good agreement with the experiments.

ACKNOWLEDGEMENT

This work was supported by the Cross-Ministerial Strategic Innovation Promotion Program (SIP): Innovative Design/Manufacturing Technologies, funded by NEDO.

REFERENCES

[1] D. Deconinck, S. Van Damme, C. Albu, L. Hotoiu, J. Deconinck: Study of the effects of heat removal on the copying accuracy of the electrochemical machining process, Electrochimica Acta 56, 5642–5649 (2011).
[2] F. Klocke, M. Zeis, A. Klink: Interdisciplinary modelling of the electrochemical machining process for engine blades, CIRP Annals - Manufacturing Technology 64, 217–220 (2015).
[3] D. A. G. Bruggeman: Calculation of various physics constants of heterogeneous substances I dielectricity constants and conductivity of mixed bodies from isotropic substances, Ann. Phys., 24, 636–64 (1935).
[4] T. Shimasaki, M. Kunieda: Study on influences of bubbles on ECM gap phenomena using transparent electrode, CIRP Annuals- Manufacturing Technology (2016).
[5] Maxwell, J.C.: A Treatise on Electricity and Magnetism, 2nd edition, Vol. 1, p. 435, Clarendon Press, Oxford (1881).
[6] R. Pal: On the electrical conductivity of particulate composites, Journal of Composite Materials, Vol 41, Issue 20, 2007.
[7] H. Tetsuya: Dielectric theory on the interfacial polarization for two-phase mixtures, Bulletin of the Institute for Chemical Research, Kyoto University (1962), 39(6): 341-367.
[8] A. Sokolichin, G. Eigenberger, A. Lapin: Simulations of Buoyancy Driven Bubbly Flow: Established Simplifications and Open Questions, AIChE Journal, vol. 50, no. 1, 24–49(2004).