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Study of Anode Shape Prediction in Through Mask Electrochemical Micro Machining

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Abstract - *Electrochemical micromachining (EMM) appears to be a promising technique, since in many areas of application, it offers several special advantages that include higher machining rate, better precision and control, and a wider range of materials that can be machined.*

Electrochemical machining for a hole is a complex phenomenon because it is involving two phase fluid dynamics, unsteady state heat transfer, electric field distribution, mass transfer, electrochemistry etc. between moving boundaries. Therefore Anode (work) shape prediction models are complicated.

This paper is reviewed different model for analysis problem ie anode shape prediction. With finite element method, the anodic dissolution process is predicted.

Keywords - *Electrochemical Machining Electrochemical micromachining, tool designing, anode shape prediction*

I. INTRODUCTION

Since miniaturization will continue as long as people require efficient space utilization with more efficient and better quality product, micromachining technology will become still more important in the future. ECMM is an electrochemical reaction of the anodic dissolution process. It is the reverse of electroplating. Surface properties of a test piece, integrated micro channels used as a drug delivery system and various aeronautical industries' requirements. Usually slots, complex shapes and micro-holes are produced in a large number in electronic industries. The several advantages of ECM no tool wear, stress-free, high throughput, smooth surfaces, and the ability to machine complex shapes in materials regardless of their hardness or whether they are heat-resistant materials. Micro fabrication by ECMM involves mask-less or through-mask material removal.

Metal removal rate (MRR) in electrochemical machining (ECM)depends upon a large number of highly interrelated parameters such as electric field distribution, electrolyte conductivity (k),temperature (T), valency of dissolution (Z), electrolyte flow velocity(V) etc. Thus ECM is a fairly complex process which involves the simultaneous occurrence of two phase fluid dynamics, conjugate heat transfer, mass transfer, thermodynamics, and electrochemistry between moving boundaries. [1]

The important characteristic of tool design in ECMM is to find the shape of the tool together with the optimum machining conditions to produce the required work shape [2]. In earlier "trial and error" methods with machining conditions is used to obtain the correct tool geometry. Such methods are expensive, time consuming, and have low accuracy. The analytical methods [3] have been proposed for anode shape prediction in ECM. Different researchers [4-8] have also developed numerical methods for determining anode shape and/or tool design in ECM.

This paper proposes computer based simulation approach for tool design based on a finite element technique, in ECMM.

II. TOOLING DESIGN

Tool Design in ECM deals basically with the computation of tool shape which under specified machining conditions would produce a work piece having the prescribed shape and accuracy since the actual tool design problems are still difficult to solve, little progress has been made in this direction. Conversely, procedures, empirical or otherwise, have been well established for the prediction of anode (or work) shape obtainable from a tool while operating under the specified conditions of machining. For anode shape prediction, different models have been developed ranging from the one based on simple principle to those based on approximate numerical techniques like finite difference technique finite element technique and boundary element technique [9].

Anode shape prediction in case of ECM with parallel electrodes is simpler than the one of electrochemical drilling of blind holes. However, different models are used to predict work profile in different zones of electrochemically drilled blind hole, viz, side transition, front, and stagnation zones.

A number of model for anode shape prediction and tooling design in ECM have been developed, ability to predict variations in IEG for any given operating conditions is a prerequisite for proper design of ECM tools and anode shape prediction.[9]

III. ANODE SHAPE PREDICTION

To analyse the variation in IEG for any operating condition is a required for proper design of ECM tools, many of these anode shape prediction models (Fig 1) are discussed in terms of the inter electrode gap. According to Tipton tool design is based on the computation of IEG for the given operating conditions. In his theory he does not consider the effects of many important parameters such as the mode of electrolyte flow and change in electrical conductivity of the electrolyte.[10] Therefore, the exact path of the electric current flow lines within the IEG is difficult to determine analytically. This is one of the reasons responsible for the difference between the analytical and the experimental results.

Konig and Paul, and Heitman have proposed a nomographic approach for anode-profile prediction. But such empirical equations and nomograms are normally valid under the specified working conditions only, which limits their use.[11] Purely analytical methods like the complex variable approach method have been proposed which cannot practically be applied to analyse the real-life problems of complex anode shapes.[12] Keeping in view the limitations of the pure analytical methods, researchers have proposed more useful models based on numerical analysis techniques (also called approximate methods) The finite difference method has been employed for tooling design in ECM. The following Laplace equation (1) has been solved for determining potential distribution in the IEG.

…(1)

From the potential distribution, the current density (J) can b evaluated using Eq(2)

…(2)

Where K is the conductivity of the electrolyte and n is the normal at a point on the work surface.

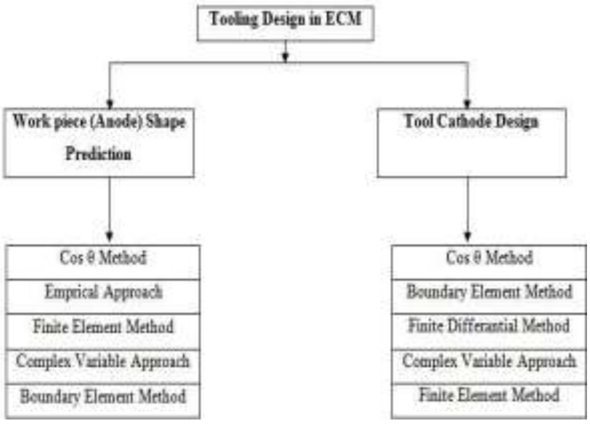

Fig. 1 Models for Tooling Design for ECM [9]

The boundary element method (BEM) using linear and quadratic is oparametric elements have been employed to solve the Laplace equation in the IEG. However, this model cannot address the non-linearities, anisotropy and inhomogeneities of the IEG. Therefore, finite element methods (FEM)seem to be the only better and comprehensive alternative [13].Step by step procedure followed for anode shape prediction is as follows [14]

- Decide whether the analysis to be made is one, two or three dimensional.
- Collect all the initial data in the proper units and, if necessary, preliminary computation (for example, flow velocity from the volumetric flow rate) is also done.
- Now, decide whether the problem is to be solved as a temperature distribution, or electric field potential distribution problem.
- The Electric field potential at different point is calculated by solving Laplace equation in one, two or three dimension as the case. This equation can be solved by one of the approximate numerical methods (FDM, FET, or BET).
- From the above Electric field potential distribution, current density is calculated at different points
- Calculate the temperature at different point and is used to modify the electrolyte conductivity. Now IEG is computed at different point in the domain of interest so that expected anode shape can be predicted.

A. *Anode Shape Prediction using FEM*

In FEM, there is a choice of the shape and size of the elements, and it is easy to incorporate different boundary conditions as well as to analyse non-homogeneous situations. Elements of different shapes and sizes are used conveniently at the same time. Two-dimensional finite element formulation for the evaluation of potential distribution in the IEG during ECM is discussed here.

In general, the electric field potential distribution within the IEG obeys the Laplace equation (1). The field vector Φ in Eq (1), should be determined in such a manner that it satisfies the boundary conditions.

$$f(\varphi) = \iint \left[\frac{1}{2}\left\{\left(\frac{d\varphi}{dX}\right)^2 + \left(\frac{d\varphi}{dY}\right)^2\right\}\right] dX dY \qquad \ldots(3)$$

Using simplex triangular elements to represent the lEG, the field variable (X, Y) can be assumed to vary linearly within the element throughout the solution domain. For such a case, we can write

$$\varphi(X,Y) = N_i\varphi_i + N_j\varphi_j + N_k\varphi_k$$
$$= [N]^e\{\varphi\}^e \qquad \ldots(4)$$

Where $\{\varphi\}^e$ is the column vector of nodal potentials for elements e. The interpolation function N_e is define as below

Where B = i, j, k, Δeis the area of an element, and a_B, b_B and c_B are defined as:

$a = X_jY_k - X_kY_i$, $b = Y_j - Y_k$, $c = X_k - X_j$, …(5)

Similarly, other terms can be evaluated in cyclic permutation of the subscripts i, j and k.The element equations, therefore, can be written as

$$\frac{df^e}{d\varphi_i} = \iint [\{(\frac{dN_i}{dX})\varphi_i + (\frac{dN_j}{dX})\varphi_j + (\frac{dN_k}{dX})\varphi_k\}\frac{dN_i}{dX} + \{(\frac{dN_i}{dY})\varphi_i + (\frac{dN_j}{dY})\varphi_j + (\frac{dN_k}{dY})\varphi_k\}\frac{dN_i}{dY}]dXdY$$

…(6)

Similarly, equations can be derived for nodes j and k of an element. Then the equations for the nodes i, j and k of an element combined together can be written in a standard form as follows:

$$\begin{Bmatrix} \frac{df^e}{d\varphi_i} \\ \frac{df^e}{d\varphi_j} \\ \frac{df^e}{d\varphi_k} \end{Bmatrix} = \quad \ldots(7)$$

Where K_m is the stiffness matrix with the following for element 1.

$$\begin{bmatrix} K_{ii} & K_{ij} \\ K_{ji} & K_{jj} \\ K_{ki} & K_{kj} \end{bmatrix} \quad \ldots(8)$$

and the coefficients of the stiffness matrix are given by

$$K_{ij}^e = \iint (\frac{dN_i}{dX}\frac{dN_j}{dX} + \quad \ldots(9)$$

Using the definition of interpolation function, it can be shown that

...(10)

The matrices for individual elements can be assembled together to give the system of equations. Reactions at the electrodes cause current density dependent overpotential. Their presence at the electrodes would alter the boundary conditions as follows:

φ = f*(J) at the cathode
φ = E – g*(J) at the anode

Where f* (J) and g* (J) are arbitrary functions for the cathodic and anodic overpotentiats, respectively. For the sake of simplicity, it has been assumed that the electrode surfaces are equipotential, which means

φ = 0 at the cathode
φ = E at the anode

After substitution of the boundary conditions, a set of simultaneous equations is obtained, which in the present case, has been solved using the Gauss elimination technique. One of the reasons for the failure in the development of an accurate anode shape prediction model is the complexity of interactions among so many parameters.

IV. MODEL & NUMERICAL METHOD

A. Model Development

The mask developed in the through-mask EMM, as shown in Fig. 2, consists of a conductive metal tool and an insulation layer. The insulation layer has the pattern which will be transferred to the anode work piece. The mask is bonded to the anode. The metal tool serves as the cathode tool. The electrolyte flows onto the surface of the mask at a high speed and fills in all features in the metal and the insulation layer. Then the areas on the anode exposed in the electrolyte would dissolve when sufficient voltage was applied. The current distribution at the electrode is thus dictated by the mask parameters. Therefore, in the calculation model, the emphasis is made on the mask parameters. Figure 2 shows the scheme of simplified through-mask EMM process used for numerical calculation in which h is the thickness of the insulating mask, d is the depth of hole.

B. Assumptions

In the proposed micromachining, the current distribution defines the profile of micro anode shape evolution. Therefore, analysis of current density has been carried out. Modeling and simulation have been done to observe the current density distribution. The assumptions were made as follows [15]:

- The current density distribution at the anode surface is determined solely by the Ohmic effects.
- The conductivity of electrolyte, k, is uniform
- The temperature of electrolyte, T, is uniform,
- Due to the ultrasonic agitation during process, the concentration gradient in the bulk electrolyte is negligible.
- Current efficient is constant during ECMM Process.

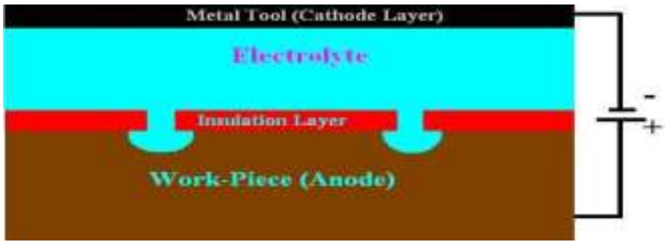

Fig. 2 Schamtic Through mask ECMM [16]

C. Boundary Condition

According to the electric field theory, the electricpotential distribution in electrolyte is governed by Laplace'sequation:
Boundary conditions are as follows [16]
According to fig 3, the potential w obeys Laplace's equation within gap domain Ω [17]

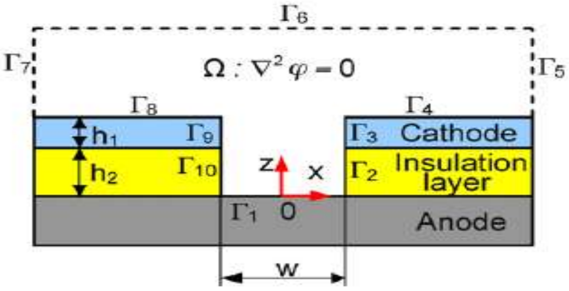

Fig. 3 Electric Potential Distribution Boundary Condition [17]

$\nabla^2 \varphi = 0$

Where   is the electric potential in electrolyte flow field.

(At the cathode Tool)
(At the anode surface)
(The boundary condition)

Where E is the voltage between the anode work piece and the cathode and n is the surface normal. The current density, i, is then given by the Ohm's law as the normal derivative of the potential, i.e

…(11)

The rate MRR, at which the anodic surface recedes, is determined as:

...(12)

Where M is the molecular weight of the anodic metal, n is the metal dissolution valence,   is the density of the anodic metal, F is Faraday's constant(96458 C/mol), and η is the current efficiency of anodic metal dissolution, which was assumed to be constant at 100%.

A. WORKING STEPS & FLOW CHART

In order to predict the anode shape evolution, the boundary of electrode surface is displaced according to current density i, using faraday's law. The program flow diagram for anode shape evolution is shown in figure 4.

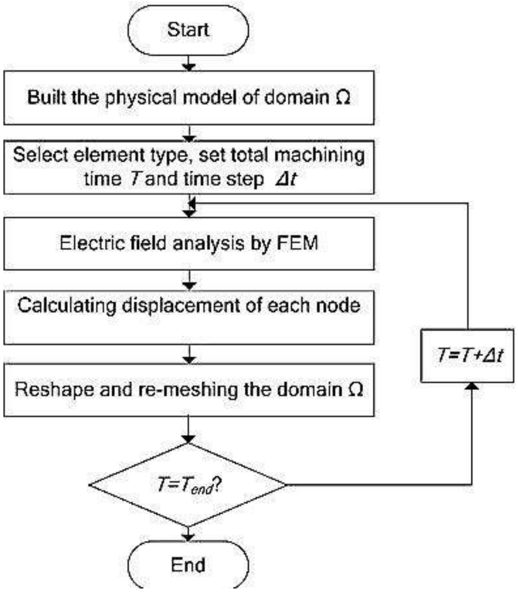

Fig. 4 Program Flow Diagram of Anode Shape Prediction for ECMM[17]

B. SIMULATION

One-dimensional, two-dimensional and three -dimensional mathematical models that were written to describe ECM processing are very difficult to solve analytically. This is because within the solution range, the interface shape between electrolyte and work piece is changing continuously due to erosion. The electrochemical process is different from other machining methods because of the lack of a selective control of erosion process. In addition, this processing takes place continuously with different speeds in all points along work piece surface. Taking in to consideration these difficulties and characteristics, a combination of a numerical solution and a graphical method was adopted to obtain the final shape of the working cathode. There are various analyzer software used for simulation of anode shape evolution such as MATLAB, Ansys, COMSOL Multiphysics, STZFET-22 etc.

C. MATLAB

For anode shape prediction, drilled straight holes with a few micrometers in diameter regulating the machining conditions, conduct an experimental analysis to predict the anode shape evolution during ECD, MRR (material removing rate) etc. Analyze the anode work piece shape obtained after ECD and make a comparative computer simulation by using Finite Element method in MATLAB PDETOOL. In MATLAB the anode shape is predicted by partial equation tool ie PDE Tool. The various step involve in anode shape prediction by MATLAB are as following.

- Experimentation on ECMM setup.

- Drilled the hole through ECD
- Discretization of the domain into a set of finite element
- Weak formulation by Gelerkin method
- Derivation of the interpolation function
- Development of F.E.M model
- Imposition of boundary conditions
- Calculation of the secondary variable
- Comparative study for the Practical Anode Shape & simulated Anode Shape of electro-chemical micromachining

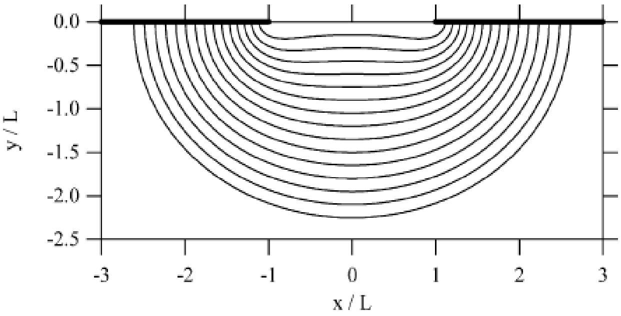

Fig. 5 2D Simulation of Shape Evolution of the Cavity [21]

D. ANSYS

Finite element method (FEM) which is suitable for problems involving uneven geometries is used as the numerical method for solution of the shape evolution problem. The commercial FEM software ANSYS is employed in which planar elements used in electric field analysis. Besides the element type, element size and computational time cycle also affect the accuracy of the computed results [18]; hence, various parameters mentioned above are adopted and the results compared with each other. The operation conditions have been determined by trial and error as follows: Element plane67 is employed and the computing domain is divided into a series of small triangular elements it is called Discretization; the time step is 0.1 s.

Current density distribution on the initially flat metal surface is shown in Fig 6. The normalized current density is defined as i/i_{max}, where i_{max}: the maximum current density and i: current density of every key point on the surface. As shown in Fig. 6, the current density distribution on each surface is uneven and the lowest current density is always on the center of the trench. The thicker the insulation layer is, the more uniform the current density distribution is observed. This non-uniform current density distribution will lead to a convex dimple profile. The thickness of the insulation layer is 100µm in the simulation. The time step is 0.2 s. With the material dissolution step by step a given cavity evolves from an initially flat shape into a hemispherical shape.

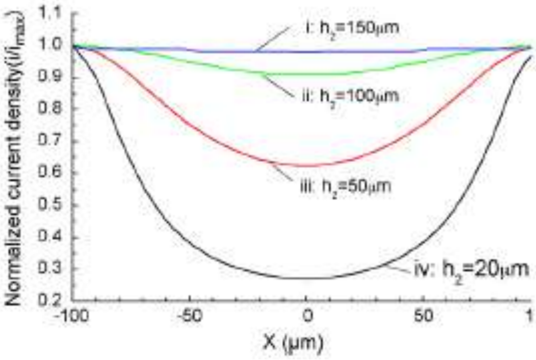

Fig. 6 Current Density Distribution on the Anode Surface[17]

E. COMSOL Multi-physics Modeling

The ECM model comprises several physical domains: Navier-Stokes flow description, electric field distribution, heat conduction & convection, gas convection and moving boundaries (work piece material removal). All constitute a metaphysics problem. Out of the real process an adequate geometry model needs to be deduced, which should be as simple as possible but comprises necessary process features according to the concrete goals of the simulation. In many cases 2D models of certain areas and symmetric geometries are leading to useful information.[20]

The ECM process was set as transient model into the COMSOL application modes "Moving Mesh" and "Conductive Media DC". Due to the permanent flow of "fresh" electrolyte, thermal effects, concentration variations, as well as material transport phenomena and fluid dynamics were neglected.

Main driver of EC erosion is the anodic dissolution of metal bonds due to an electric charge transport Q following Faraday's law. The removed material volume V is calculated by

$$V = \eta \cdot \frac{M}{\rho \cdot Z \cdot F} \cdot Q$$

M is the molar mass, the density, Z the electrochemical valence of the material, F the Faraday constant, and η is the current efficiency. The velocity of material removal in normal direction Vn depends on the current density in normal direction Jn:

$$V_n = \eta \cdot \frac{M}{\rho \cdot Z \cdot F} \cdot J_n$$

Most influencing parameter for the material erosion is the electric field E since it affects the current density proportionately:

$$J = \sigma . E$$

The mesh was generated using the automatic mesh creator with the option "Extra fine”.

When the machining time increases, the depth of the erosion is enlarged significantly. The hole depth increases while the time increases. However, the erosion depth produced by a stationary electrode.

At the beginning, the cavity is shallow and the gap between the electrode and the workpiece is small. During the process, the erosion gets deeper and the gap becomes larger, which will slow down the machining process by decreasing the electric field intensity as shown by Eq 13 below

…(5.1)

So overall normal current density is decreases ie material removal rate is decreases.

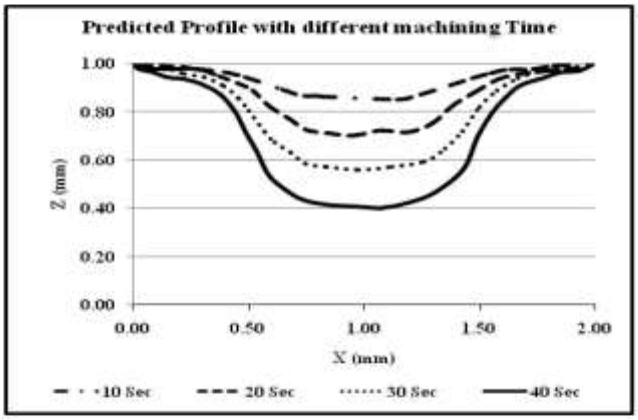

Fig. 7 Current Density Distribution on the Anode Surface[20]

V. RESULT & DISSCUSSION

There is little variance in computed results with different element types while the element size and time interval present appreciable variance in values of the computed results. The discussion so far has been limited to the current distribution at the initial electrode surface. In through-mask EMM, it is essential to consider the current distribution within the evolving cavity according to Faraday's law. The discussion so far has been limited to the current distribution at the initial electrode surface. The results show that the current distribution at the initial metal surface is highly non-uniform and the maximum of the current density occurs at the intersection of the metal surface and the mask. Since the metal removal rate is proportional to the local current density, the maximum vertical displacement of the metal surface is away from the center of the feature.

The large over cut at and near the top surface of the workpiece is attributed partly to the stray current attack and partly to the fact that the period of electrochemical dissolution is maximum at the top and minimum at the bottom. The time of dissolution would vary linearly from top to bottom.

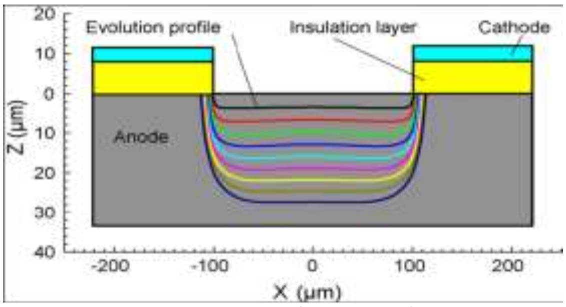

Fig. 8 Shape Evolution of Anode Surface [17]

VI. CONCLUSSION

Simulation is a powerful tool for the design and improvement of electrochemical processes. It provides information for an optimization of the electrode design for achieving the intended workpiece geometry and it can propose process parameters, such as voltage, electrode velocity, or electrolyte pressure. Instead of an iterative tool and process design an FEM simulation can be an effective shortcut which reduces time and financial effort. Additionally, it visualizes the ECM process.

Process simulation is a technique to support the manufacturing engineer's experience for reduced lead time, lower cost, increased product quality and better understanding of the process.

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