Finite-Element Simulation of dimensional limitation of Electro Chemical Machining (ECM) Process

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***Abstract*— Electrochemical Machining (ECM) has established itself as one of the major alternatives to conventional methods of machining difficult - to - cut materials of and/or generating complex contours, without inducing residual stress and tool wear. The need for complex and accurate three dimensional (3-D) micro components is increasing rapidly for many industrial and consumer products. Electrochemical machining process (ECM) has the potential of generating desired crack-free and stress-free surfaces of micro components. This paper reports a study of pulse electrochemical micromachining (PECMM) using ultra short (nanoseconds) pulses for generating complex 3-D microstructures of high accuracy. A mathematical model of the micro shaping process with taking into consideration unsteady phenomena in electrical double layer has been developed. The software for computer simulation of PECMM has been developed and the effects of machining parameters on anodic localization and final shape of machined surface are presented.**

Keywords– Finite-Element, ECM, Dimensional, Machining, Temperature Field and Cell

I. INTRODUCTION

Electrochemical machining (ECM) also uses electrical energy to remove material. An electrolytic cell is created in an electrolyte medium, with the tool as the cathode and the workpiece as the anode. A high-amperage, low-voltage current is used to dissolve the metal and to remove it from the workpiece, which must be electrically conductive. ECM is essentially a deplating process that utilizes the principles of electrolysis. The ECM tool is positioned very close to the workpiece and a low voltage, high amperage DC current is passed between the two via an electrolyte. Material is removed from the workpiece and the flowing electrolyte solution washes the ions away. These ions form metal hydroxides which are removed from the electrolyte solution by centrifugal separation. Both the electrolyte and the metal sludge are then recycled.

Unlike traditional cutting methods, workpiece hardness is not a factor, making ECM suitable for difficult-to-machine materials. Takes such forms as electrochemical grinding, electrochemical honing and electrochemical turning. Electrochemical deburring is another variation on electrochemical machining designed to remove burrs and impart small radii to corners. The process normally uses a specially shaped electrode to carefully control the process to a specific area. The process will work on material regardless of hardness.

Advantages of Electrochemical Machining (ECM):

i. The components are not subject to either thermal or mechanical stress.
ii. There is no tool wear during electrochemical machining.
iii. Non-rigid and open work pieces can be machined easily as there is no contact between the tool and workpiece.
iv. Complex geometrical shapes can be machined repeatedly and accurately
v. Electrochemical machining is a time saving process when compared with conventional machining
vi. During drilling, deep holes can be made or several holes at once.
vii. ECM debarring can debar difficult to access areas of parts.
viii. Fragile parts which cannot take more loads and also brittle material which tend to develop cracks during machining can be machined easily through Electrochemical machining
ix. Surface finishes of 25 μ in. can be achieved during Electrochemical machining

The objective of this work is to develop a silent, low-impact, low vibration, low temperature technique to cut a 5-inch diameter access hole through sheet metal (nominal thickness, 1.5 mm) in 10 minutes or less. The equipment for doing so must be self-contained, lightweight (man portable, below 100 lb) and readily transportable. The metal may be mild steel, stainless steel, tool steel or non-ferrous metals such as brass, copper, aluminum or titanium, etc. The technique must accommodate plate thickness of 1 cm.

Electrochemical machining was chosen for this application. Electrochemical machining is a technique whereby metals are cut, shaped and polished by the passage of anodic current through the metal work piece (the anode, grounded), across an electrolyte gap, and into a second metal electrode (the cathode).1 The rate of cutting is independent of the hardness of the metal, and to a first approximation is independent of the identity of the metal or alloy. The cut replicates the geometry of the cathode.

ECM is often characterized as "reverse electroplating," in that it removes material instead of adding it.It is similar in concept to electrical discharge machining (EDM) in that a high current is passed between an electrode and the part, through an electrolytic material removal process having a

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negatively charged electrode (cathode), a conductive fluid (electrolyte), and a conductive workpiece (anode); however, in ECM there is no tool wear.[1] The ECM cutting tool is guided along the desired path close to the work but without touching the piece. Unlike EDM, however, no sparks are created. High metal removal rates are possible with ECM, with no thermal or mechanical stresses being transferred to the part, and mirror surface finishes can be achieved.

In the ECM process, a cathode (tool) is advanced into an anode (workpiece). The pressurized electrolyte is injected at a set temperature to the area being cut. The feed rate is the same as the rate of "liquefaction" of the material. The gap between the tool and the workpiece varies within 80-800 micrometers (.003 in. and .030 in.) As electrons cross the gap, material from the workpiece is dissolved, as the tool forms the desired shape in the workpiece. The electrolytic fluid carries away the metal hydroxide formed in the process.

Because the tool does not contact the workpiece, its advantage over conventional machining is that there is no need to use expensive alloys to make the tool tougher than the workpiece. There is less tool wear in ECM, and less heat and stress are produced in processing that could damage the part. Fewer passes are typically needed, and the tool can be repeatedly used.

Electrochemical machining (ECM) is based on a controlled anodic electrochemical dissolution process of the workpiece (anode) with the tool (cathode) in an electrolytic cell, during an electrolysis process. (Fig.1)

Some of the very basic Applications of ECM are listed below:

- It can be used for Die-Sinking operations.
- Drilling a jet engine turbine blade.
- Multiple Hole drilling.
- Steam turbine blades can be machined within close limits.

Electrolysis is the name given to the chemical process which occurs, for example, when an electric current is passed between two electrodes dipped into a liquid solution. A typical example is that of two copper wires connected to a source of direct current and immersed in a solution of copper sulfate in water as shown in Fig. 2.

An ammeter, placed in the circuit, will register the flow of current. From this indication, the electric circuit can be determined to be complete. It is clear that copper sulfate solution obviously has the property that it can conduct electricity. Such a solution is termed as electrolyte. The wires are called electrodes, the one with positive polarity being the anode and the one with negative polarity the cathode.

The system of electrodes and electrolyte is referred to as the electrolytic cell, while the chemical reactions which occur at the electrodes are called the anodic or cathodic reactions or processes.

A typical application of electrolysis is the electroplating and electroforming processes in which metal coatings are deposited upon the surface of a cathode-workpiece. Current densities used are in the order of 10^{-2} to 10^{-1} A/cm2 and thickness of the coatings is sometimes more than 1 mm. An example of an anodic dissolution operation is electro polishing. Here the workpiece, which is to be polished, is

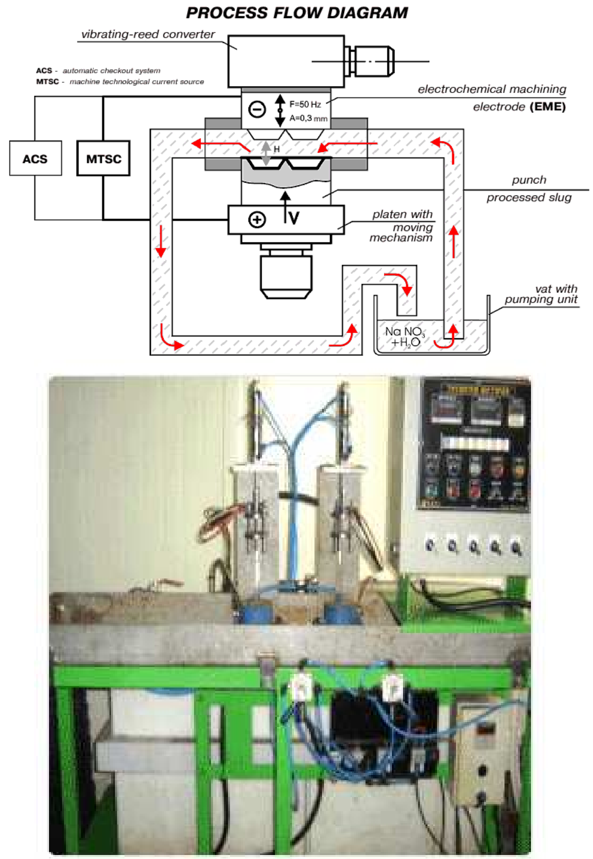


Fig. 1: Electron Beam Machining (EBM) Process

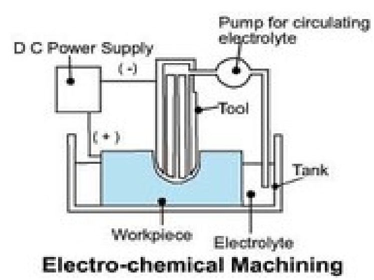


Fig. 2: Electrochemical cell

made the anode in an electrolytic cell. Irregularities on its surface are dissolved preferentially so that, on their removal, the surface becomes smooth and polished. A typical current density in this operation would be 10^{-1} A/cm2, and polishing is usually achieved on the removal of irregularities as small as 10 nm. With both electroplating and electro polishing, the electrolyte is anodic dissolution process in which a direct current with high density and low voltage is passed between a workpiece and a reshaped tool (the cathode). At the anodic workpiece surface, metal is dissolved into metallic ions by the depleting reaction, and thus the tool shape is copied into the workpiece.

The electrolyte is forced to flow through the inter electrode gap with high velocity, usually more than 5 m/ s, to intensify the mass/charge transfer through the sub layer near anode and to remove the sludge (dissolution products e.g., hydroxide of metal), heat and gas bubbles generated in the gap. In typical manufacturing operations, the tool is fed toward the workpiece while maintaining a small gap. When a potential difference is applied across the electrodes, several possible reactions can occur at the anode and cathode.

II. EXPERIMENTAL BASIS OF ELECTROCHEMICAL MACHINING

Theoretical Basis of Current distribution; the current flow and the shape of the cut is determined to a good approximation by solution of Laplace's equation ($\nabla 2\Phi = 0$), between two potential surfaces. This current distribution is independent of electrolyte conductivity and is called "primary" current distribution. Current distribution will be controlled by the dimensions of the smaller electrode, at which surface the lines of current flow are close together. The first correction on this model (called "secondary" current distribution) includes boundary conditions that reflect the voltage drop across the surface of the electrodes resulting from kinetic resistance of the electrochemical reactions. These boundary conditions tend to make the current flow more uniformly across the larger electrode than might be predicted by primary current distribution. For a general discussion of potential and current distribution in electrochemical systems, the chemical properties of the electrolyte may benefit current distribution. A localization of current flow to smallest dimensions of the anode is desirable to minimize the time required for cutting at a fixed current. Certain oxidizing electrolytes (such as sodium chlorate, the one used in this work) achieve this by chemically oxidizing the surface of many metals in the vicinity of the cut, resulting in local passivation. This passivation tends to concentrate the flow of current to the part of the work piece directly opposite the cathode, where the fields are strong enough to overcome the passivation.

Thus the cutting is focused to form a narrow trench.

Of particular interest is the research leading to the use of sodium chlorate electrolytes for applications in automotive manufacturing.

The throwing power (or focusing of cutting action) was maximized with the use of the chlorate, because of the formation of distinct active, passive and transpassive regimes having distinct electrode potentials and spatial distribution relative to the cathode.

Finite elements simulations are done in 3 steps with the main pieces:

1- Modeling by FEMB

2- The thermal study and processing

3-Post-Processing result of analysis by ANSYS software for results discussion

Finite-Element Modeling of SAW shows in Fig. 3.

The differential Equations (1) – (2) are solved iteratively by the SIMPLEC numerical procedure:

For boundary condition of fluid field:

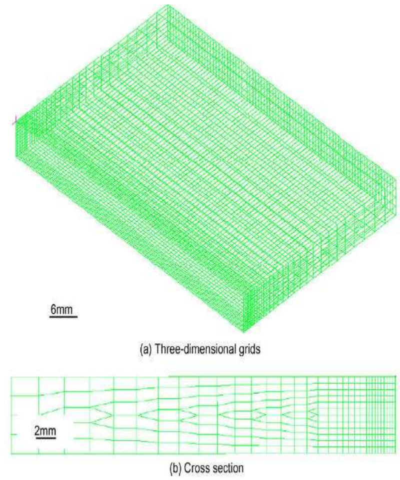


Fig. 3: Finite-Element Modeling of ECM

$$\int_{\Omega} \partial P[\frac{1}{C^2}\ddot{P} + (\nabla)^Y \nabla P] d\Omega + \int_{T_1} \partial P n^T \ddot{u}\, dT + \int_{T_3} \partial P \frac{1}{g} \ddot{P}\, dT = 0 \qquad (1)$$

For boundary condition of solid field:

$$\int_{\Omega} \partial u [P_s \ddot{u} + S^T DSu] d\Omega - \int_{T_1} \partial u^T \bar{t}\, dT = 0 \qquad (2)$$

The need for complex and accurate three dimensional (3-D) micro components is increasing rapidly for many industrial and consumer products. Besides traditional machining techniques such as micro turning and milling, attention is being focused on non-traditional machining techniques such as micro electrical discharge machining (EDM) and micro electro chemical machining (ECMM) and laser machining because of their unique characteristics. Electrochemical machining (ECM) is based on controlled anodic dissolution process of the workpiece (anode) with the tool as the cathode in an electrolyte cell. The ability of ECM in rapidly generating a stress-free and crack-free smooth surface on any electrically conductive material (irrespective of hardness) makes it an excellent choice as a micro production process. Micro shape of element is achieved by controlled movement of tool electrode along specified path (Fig. 4).

However during ECM material is removed also from zone which is far away from tool electrode due to stray current. It is particularly important in micromachining, because dimension of this zone may be larger than the dimension of produced microstructure. Increase of the localization of electrochemical dissolution (stop dissolution on surface not under tool electrode) is an important problem in EC micromachining with tool electrode, especially a universal tool electrode.

This problem was solved successfully by researchers from Max-Planck Institute in Berlin by using ultra short pulses with pulse on-time below 200 ns. It was found that main factor determining the localization of electrochemical dissolution is phenomenon connected with charging the electrical double layer. They showed possibility of geometrical nanostructure fabrication with picoseconds pulse.

III. PHYSICAL MODELING

The ECD process is based on electrolysis. The drill is a conducting cylinder with an insulating coating on the outside.

This drill is lowered into the material with a certain speed *s* while a voltage *U* is applied to it. In this way a cylindrically shaped hole is obtained as illustrated in Fig. 2. Because of the axisymmetry we can essentially use two dimensional computational models. We assume that the electrode is already in the anode material. The coordinate system is chosen relative to the fixed anode. Another reasonable option might be choosing this system relative to the moving drill, since all the important physical processes take place near the tip of the electrode.

The corrosion of the anode surface is a direct result of electrolysis. This is a process where an electric potential difference is imposed on an anode and a cathode. The electrolyte, often a sulphuric acid, tends to corrode the anode surface in this electric field. The thus corroded material is removed by the electrolyte flow.

IV. SIMULATION RESULTS

In Fig. 5 the results of a simulation run are presented. At intervals of 50 secs the shape of the boundary is displayed. The computations have actually been carried out for the right half of the domain only, since we have a symmetric geometry (see Fig. 5). In this case the shape of the tabulators is not very pronounced. By changing the process parameters other shapes may be achieved. Also differently shaped electrodes produce different holes (see Fig. 6). This is not only due to the size of the electrode, but also due to the thickness of the insulating coating on the outside of the electrode. Instead of mirroring our 2D axisymmetric results we can also apply a rotation to the cross section and obtain a 3D body as illustrated in Fig. 9. The only way to validate our model is comparing the obtained geometry from a simulation run with an X-ray of a drilled hole in production (see Fig. 1). But even then, due to the complex shape, it is difficult to compare them. In order to demonstrate the validity of the model an experiment has been performed with step-wise variation of the potential difference. Its result is compared with the result of the simulation.

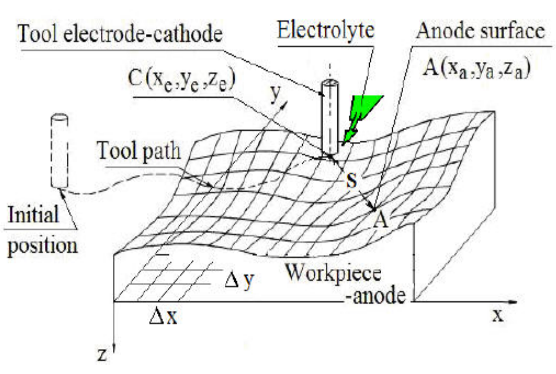


Fig. 4: Scheme of Pulse Electrochemical Micromachining

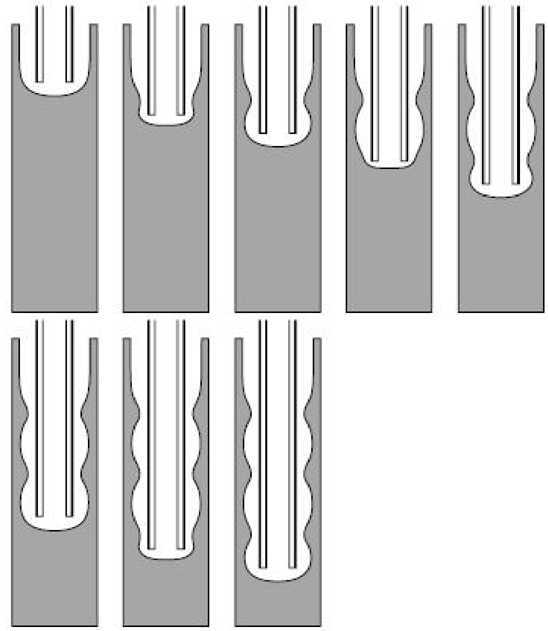


Fig. 5: Deformation of the anode surface

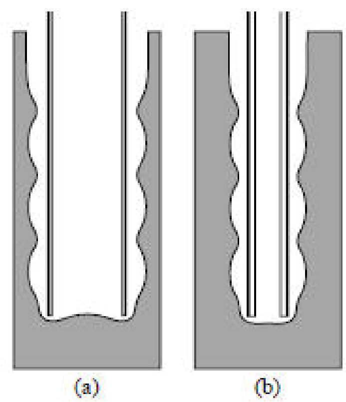


Fig. 6: Different types of electrodes

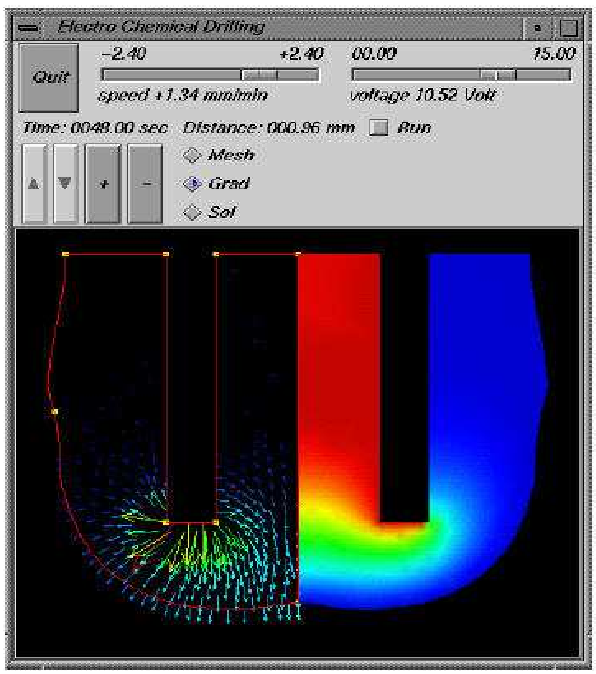
V. DESIGN OF A REAL TIME SIMULATION SYSTEM

A particularly important feature of computer based simulations concerns the methods offered for interacting with the process and for retrieving data generated during the simulation. From this point of view one can distinguish between three large classes of simulation systems: non-interactive systems, interactive visualization systems and fully interactive systems.

Non-interactive systems are the most common ones: the system operates as a pipeline having the problem definition phase (D) as the first step, followed by the numerical computations (problem solving) phase (C) and finally the result visualization phase (V). The three stages are loosely coupled.

Generally they consist of separate applications communicating solely via files. The interactivity of such a system is practically inexistent; therefore the user is obliged to simulate a time dependent process by running the same pipeline over different sets of input data corresponding to different time instants.

Another example is the ECM simulation process (see Fig. 7). The user can interact with the running drilling simulation changing the drilling voltage and speed at any moment of the process by moving the respective sliders. The computational domain has been mirrored and displays different quantities in each cross section for each time instant. The user can also change the camera's viewing parameters during the simulation (focusing, for example, on the drill's tip while this one is continuously descending). Monitoring and interacting with the ECM process is very easy and intuitive in this way.



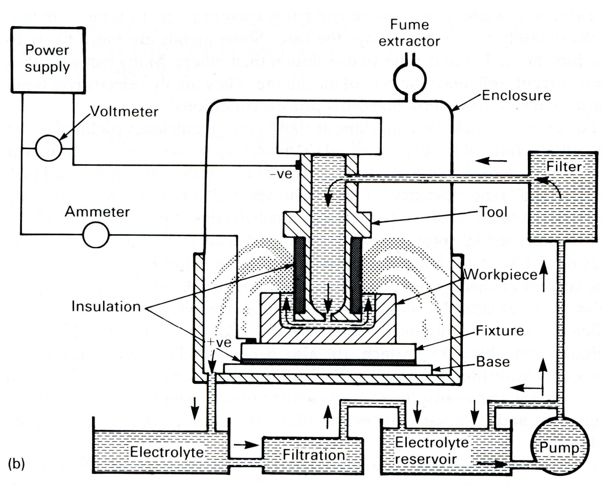


Fig. 7: Real time simulation with user interaction

VI. CONCLUSIONS

Study of micro-ECM process demonstrate that an ECM using small gap and pulse current, and a laser assistance of ECM can be effectively used for improving of micro-machining processes by increasing localization of anodic dissolution and increase of metal removal rate.

Transient phenomena connected with charging and discharging electrical double layers, which exists on boundaries: workpiece – electrolyte and tool electrode – electrolyte have important role in electrochemical micromachining with ultrashort pulses.

The developed mathematical models and software for simulation of electrochemical micromachining with ultrashort voltage are useful for analysis of electrode potential, dissolution current and electrical charge during PECMM machining with set conditions and allows determination of the influence process conditions on the localization of anodic dissolution and performance characteristic of PECMM. The developed software for simulation of micro shaping is useful for PECMM process analysis, surface shape prediction and optimization.

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