Simulation of The Electrochemical Machining Process

Authors: R. Temur T. Coole and C Bocking

Centre for Rapid Design and Manufacture (CRDM)
Buckinghamshire Chilterns University College

ABSTRACT

Electrochemical machining (ECM) or erosion, is a process for shaping materials by means of the anodic dissolution of a work-piece using suitably shaped cathodes? However, the predictability of the process is poor due to current density variations over the electrode contour leading to poor dimensional tolerances.

This paper describes how the process can be entirely simulated by computer. A model of the electric field during erosion is constructed based on the Laplace equations for the field. From the distribution of the electric field, it is possible to continuously calculate the current density at each point on the work-piece for the whole machining process. In this way, it is possible to predict the final work-piece contour by running the simulation program instead of the real process. Simulations for cylindrical, conical and spherical electrodes were carried out and compared to actual eroded parts.

ADVANTAGES AND PRESENT APPLICATIONS OF ECM

Unconventional machining processes are increasingly being used for manufacturing special steels, ceramics, plastic materials and composites. All these materials generally find applications in aerospace, automotive, electronics and electromechanical industries. In the last 20 years many technological developments have been made in order to improve the potential of unconventional applications and also the knowledge database regarding the electrochemical erosion process [1,2,3,4,5,6,7,8]. Science and engineering development has presented many challenges for the metal processing industry. Today, there is a big need to develop better processing methods and improve on current methods. These methods should reduce the cost of fabrication and should solve many of the difficult processing problems generated by the uses of new materials.

What were once unconventional methods, such electro-discharge machining, and laser processing, are nowadays used to produce high complexity parts in many applications from different processing industry. Using unconventional methods has given a big advantage in reducing the total number of operations needed for complete execution of a part. Also this has given a reduction in reject parts and an easy implementation of computer control.

Although the majority of unconventional methods have a relatively low processing speed, certain factors make them attractive:

- Removal of material is not dependent on the hardness of work-piece
- The tool can be less hard than the work piece
- The wearing of the tool is negligible.
- There is no mechanical contact between tool and work piece and parts free of distortions and internal stresses can be made.
- The secondary products produced during processing can be easily removed
- Self-checking and feedback loops can be easily implemented in the processing system
- Adaptive control strategies can be applied.

The main advantages of electrochemical erosion processing are:

- A easy way to manufacture hard materials
- This method will not produce residual internal stress in the work piece
- The possibility of producing many parts without distortion
- A relatively good speed of processing (~ 1mm/min)
- A good surface finish can be achieved (0.1 up to 10 μm).

DISADVANTAGES

The process of designing tool-electrodes in order to obtain the correct current distribution and thus shape is empirical and a scientific level has yet not been reached. Currently, the design and testing of complex shaped tools is undertaken by “trial and error”, a very expensive and time-consuming process. Handling and using a large volume of electrolyte together with the increased probability of corrosion are more problematic for the electrochemical erosion process.

OBJECTIVE OF THIS PAPER

This paper describes the development and verification of a graphical-analytical method for simulating the electrochemical erosion process. This will allow accurate predictions of work piece shape without “trial and error”, saving time and cutting costs for research. The big challenge was to identify the mathematical model that described the process and to select those parameters with greatest effect on the process. Finally it was necessary to solve this mathematical model in order to predict the shape of the tool electrode and thus the work piece.

An analytical solution for this problem is complicated by a large number of parameters that are interacting with each other and by a straight interdependence of these parameters. The tool shape required to obtain a final part having a precisely defined profile can be calculated using a number of mathematical models. These existing models simplify the real situation and can lead for inexact results especially when complicated shapes are involved.

A computer based method for the design process, based on the finite element method and using simulation, was recently proposed for electrochemical erosion process [9]. The work presented here builds on this and addresses some of the deficiencies of previous simulations. A computer program was developed which presents a graphic simulation on the screen (two-dimensional or three-dimensional) for specific operations of the electrochemical machining process. This program was developed using C program language and a solid modeller named Silver Screen. The system was divided in three main modules, simulation of the process, design tool electrode and verification of tool designed. The simulation shows on the screen the graphical effects of tool stepping on the work piece. A verification module determines automatically if the processing operation will produce the work piece with the desired dimension and shape.

MATHEMATICAL MODEL OF ECM USED IN THE SIMULATION

For a complete determination, the mathematical model for an ideal electrochemical process has to be written. Thus if f_a = anode shape at any instant during processing then it is possible to establish the evolution of the shape of the work piece:

$$f_a = F(x, y, t)$$

With some simplification assumptions, the evolution of the processed surface is given by [10]

$$\begin{cases} \dfrac{\partial F}{\partial t} = \dfrac{? \cdot \frac{K}{?} \cdot ?_e \cdot \left|grad\ U\right|}{\cos\ (n, f_a)} - \dfrac{d\ Y_s}{d\ t} \\ \dfrac{\partial^2 U}{\partial x^2} + \dfrac{\partial^2 U}{\partial y^2} = 0 \\ \dfrac{\partial U}{\partial n}\Bigg|_{isol} = 0 \\ F\ (x, y, 0) = F_0 \\ U_{(E)} = 0 \quad , \ U_{(F)} = U \end{cases}$$

where $U(x, y)$ - is electrical potential in working area

x, y - mobile co-ordinate system with respect to the tool electrode

$?_e$ - electrochemical equivalent

Y_s - dynamic equation for ECM tool, in a fixed co-ordinate system in the case of tool moving with constant speed

$$Y_s = v_s \cdot t$$

F_0 - initial shape of the anode (work piece), all other elements being already defined

K - processing constant.

$?$ - electrolyte density

Applying a discrete approach from a time point of view and assuming that the elementary time interval is Δt, the solution for the equation set is reduced to a sequence of Laplace equation solutions. After solving this set of equations and determining components for the gradient vector of the anode potential, each individual point on the anode is moved accordingly in the processing direction and in this way the evolution of the surface geometry with respect to time is obtained. Subsequently, this initial anode shape will be modified by a correction based on work parameter changes.

This procedure is repeated in order to obtain the final shape for the work pieces using this step by step approach. At the completion of the virtual processing time, if errors exist between the desired shape for work piece and the shape obtained, it is possible to incorporate into the above algorithm a new correction routine to obtain the desired tool profile.

This routine is the basis of the computer simulation program designed for the electrochemical erosion process and tool design program for the cathode.

THEORETICAL CONCEPTS OF ECM 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.

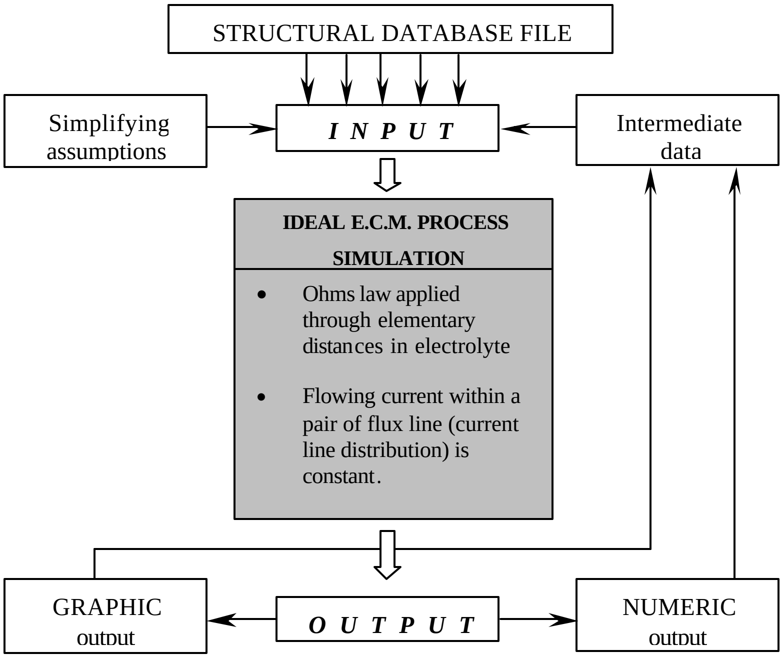

Figure 1. Schematic diagram of the simulation program.

The tool simulation program designed in this work has a main core that operates using an ideal electrochemical process. The data obtained with this base procedure, named SimEcmId was used as input data for connected procedures that translate the process from an ideal situation to a real one. There have been many attempts to use a numerical computer methods to obtain data about ECM processing, for different work conditions, but this new program has a set of improvements that allow results much closer to the real process to be obtained.

The first, general block scheme of the simulation program is presented in figure 1. From this schematic we can see that the simulation program will take input data from a structural database file that contain all the characteristic parameters for a simulation of an electrochemical process. Running this program is carried out under a set of simplification assumptions that are presented below.

Simplification assumption

All the assumptions made for this process were derived after theoretical studies on the electrochemical process. These assumptions have simplified writing and solving the mathematical model for this complex process. The main simplification assumptions were for the electrolyte properties and for the flow type of electrolyte.
Referring to the ideal model for an electrochemical erosion process we can state following assumptions:

- The electrolyte consist of a two phase one-axial flow,
- Hydrogen accumulation does not occur in the electrolyte during processing,
- Hydrogen released in the process obey ideal gases law

- The electrolyte is assumed to be an incompressible fluid
- The effect of secondary products on the electrolyte is neglected
- Two phase flow of the electrolyte is modelled as pseudo-Newtonian fluid, with a turbulent flow in working gap that will produce a complete mixing of the electrolyte.
- Increase of electrolyte temperature is the main result of Joule effect heating. This heating is generated by the electrical current flowing through the gap filled with electrolyte
- Increasing of the electrolyte temperature due to viscous dissipation of energy is neglected
- No heat transfer between electrodes and electrolyte was taken into consideration
- The heating produced by the voltage drop on electrode surfaces, due to over-potential, is considered to be taken by electrolyte
- The surface of the tool-electrode and work-piece are considered equal-potential surfaces

DESCRIPTION OF THE SIMULATION PROGRAM

General principles

The core of the simulation program, SimEcmId, was created starting from two main simplification assumptions for the electrochemical erosion process. If the potential and current distribution within the gap is in accordance with Laplace equations, these two assumptions are:

- Ohm's law applies through the elementary distances in electrolyte
- Flowing current within a pair of flux lines (current line distribution) is constant.

The first assumption eliminates the limitations of previous simulation programs based on "cosines" theory, and the second one asserts continuity of current flowing based on which "Continuity" theory was developed. To see the implementation of above assumption into the simulation procedure of an ideal process, both theories are presented and also the improvements of these theories in the simulation program described in this paper.

For a geometrical configuration of a tool-electrode boundary chosen from the database input file, two elementary columns were considered within the anode with area *b* and unitary depth. These two columns are positioned with the longitudinal axis parallel to tool feed direction, as is shown in figure 2. For the boundary of the tool-electrode and the work-piece, the following condition is true:

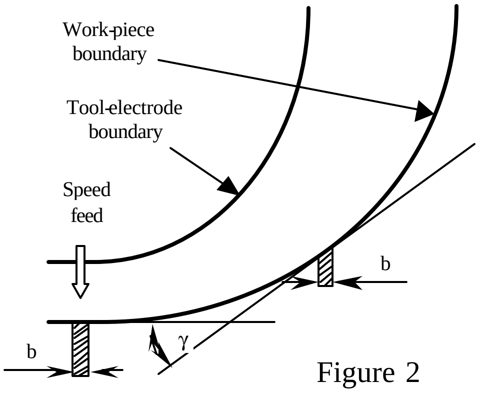

Figure 2

$$U = constant$$

For the case of processing in equilibrium conditions, an ideal electrochemical process, all work-piece boundaries will move down with the same speed. Thus the same metal volume will be removed from both columns. We can say that both columns must have the same current (I). Nevertheless, the area of one column is *b* and the area of the other column is $b/\cos ?$. Consequently, the current density will be J and $J\cos g$ respectively. Because flux current lines are perpendiculars the results from Ohm law is that also tension normal gradient should obey the same rate as current density. The boundary condition on the surface of work-piece is:

$$\left[\frac{\partial U}{\partial n}\right]_g = \left[\frac{\partial U}{\partial n}\right]_{?=o} \cdot (\cos ?)$$

The simulation program SimEcmId uses these boundary conditions and also simplification assumptions that state that Ohm's law is applicable between two corresponding points from work and tool surfaces. Thus, the gap-measured perpendicular on work-piece is inversely proportional with the cosine of angle representing bending of work surface with respect to the feed tool direction – see figure 3.

The Limitation of this approach refers to the bending angle of the work surface, which cannot be greater than 60° and about the radius of curvature of the work surface, which should be at least one order of magnitude greater than the size of inter-electrode gap. These limitations are a direct consequence of the simplification assumption made regarding application of Ohm's law. The effect of this wrong application is that a unitary current flow between the tool and work-piece through a straight conductor of electrolyte with a constant cross section had to be considered.

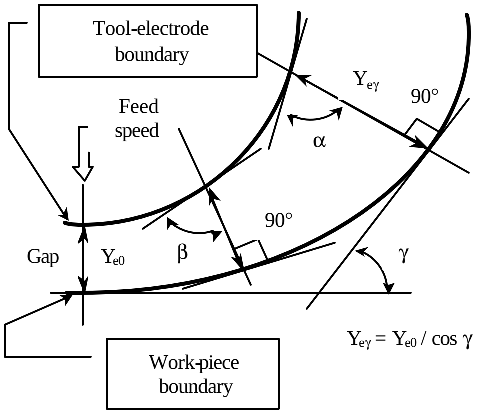

Figure 3

The correct principles on which to construct the potential field between the two electrodes are:

- Equi-potential lines and flux lines are an orthogonal curve set
- The current flowing within a pair of flux lines is constant anywhere in this field

In order to implement above first principle, in the simulation program design, the electrolyte conductor wasn't considered straight but of having a curvature and a variable cross-section. This new shape of electrolyte conductor is described by electric field equations and is an important improvement included in the electrochemical erosion simulation program presented here.

This new approach allows the elimination of simplifications and incorrect determinations presented in figure 3 where the current lines have a correct (90°) angle with only one equal-potential line. This line is the boundary of the work-piece and the remaining equal-potential lines (including here boundary of tool-electrode) have angles different from 90°, as is presented in figure 4.

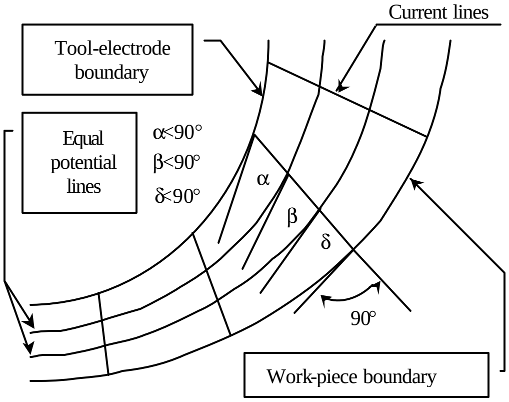

Figure 4

In order to obtain a curved shape of the flux areas with variable cross section, described by the equation $\nabla^2 f = 0$, a spline graphical primitive type was used. Then this spline primitive had tangency conditions added at both ends: the work-piece surface and the tool-electrode surface. Those tangency conditions were applied for normal lines on the surface of the tool and work-piece as nodes used in the simulation as presented in figure 6.

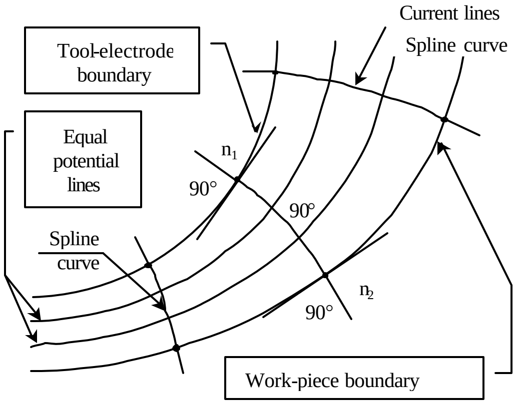

Figure 5

In this way it was possible to correct α,β,γ angles from figure 4 to 90° angles and keep to the principle which states that current lines and equal-potential lines should be orthogonal. Also with this improved approach, the flux section became variable and we can assume that the modelling of electric field between the two electrodes is more accurate and match closer to reality

Determination of work-piece profile

The principle used for the determination of the shape of the processed piece is presented in figure 7 where for each calculation step, a graphical description (for a particular case of a spherical tool electrode) is also given. Input dimensions and parameters assumed at the beginning of the simulation are available for the entire process. The contour defined by the anode surface, cathode surface and isolated side surface represent the starting point for the calculations. For this geometrical configuration, the intensity of electric field on the anode surface is calculated.

Based on this intensity and with the help of electrolyte conductivity at each point considered on anode contour, the current density and effectively the volume of material removed is determined. In the next step the mass of metal removal, in a direction normal to the anode surface and at each node considered, can be calculated for a specific time interval. The next anode contour will be in

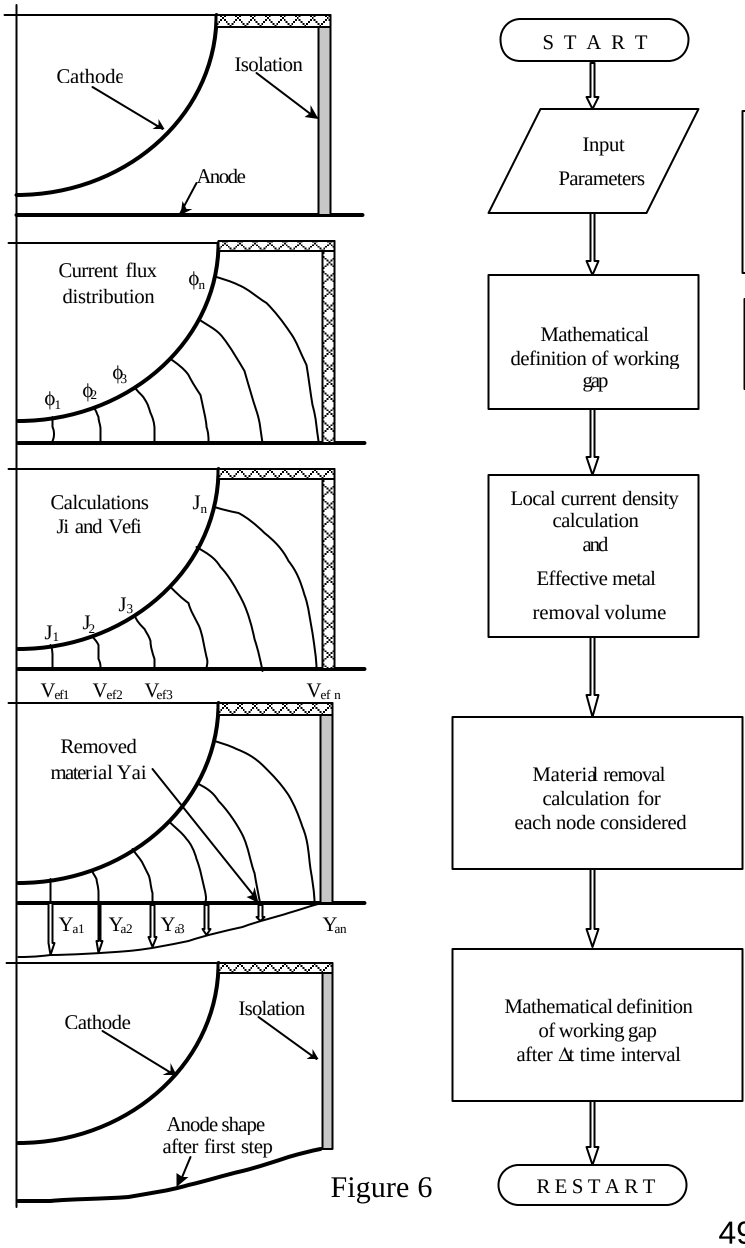

Figure 6

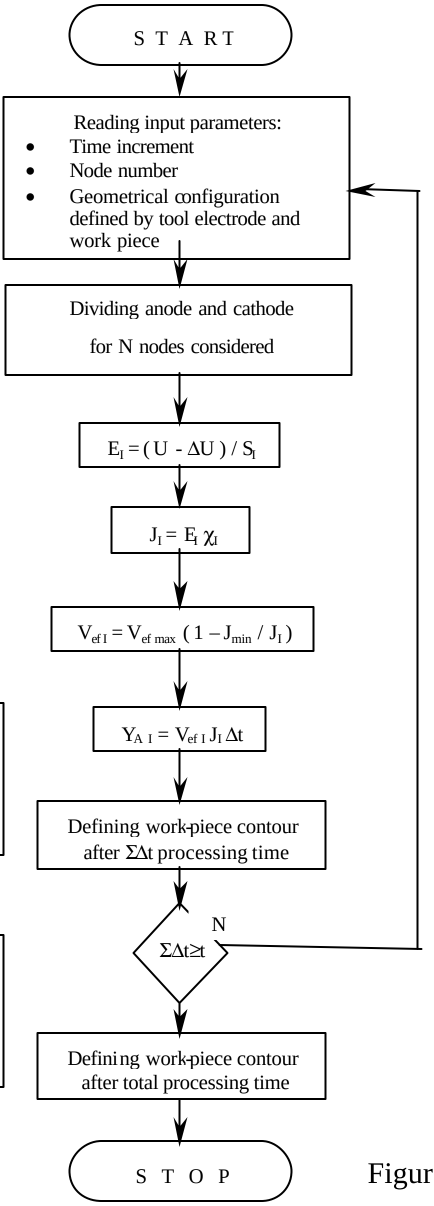

Figure 7

this way described by all n individual points obtained after the metal removal calculation. Once the new position and shape of anode contour is available then mathematical description of inter-electrode area for next simulation step is possible.

Calculation of each point erosion – logical scheme

Based on the principles presented above, the logical scheme shown in figure 7 was developed for a complete solution of work-piece contour calculation. Time interval Δt is given as a fraction of the entire processing time and the number of nodes is dependent on the desired accuracy required for the work-piece contour. After subdividing the inter-electrode gap, based on node number and drawing of current lines normal to the tool and work-piece, calculation of the local surface electric field intensity is carried out. Next, the local current density J_i, is determined and thus the effective anode metal removal volume, V_{ef_i}, together with the magnitude of the metal removal at each node Y_{A_i}, in a normal direction to the work piece. With all points determined by the metal removal calculation, a new anode contour is mathematically described. The last stage is to verify if processing depth was reached or if the processing time is finished. If at least one of these verification fails the new geometric configuration tool-piece is determined by moving the tool towards the work-piece at the appropriate feed speed.

SIMULATION RESULTS

Three elementary tool shapes were used for verification of the simulation procedure described. These shapes are cylindrical, conical and spherical and the parameters set for each simulation are presented below.

Cylindrical tool-electrode

The cylindrical tool-electrode used had following dimensions:

- Radius - 15 mm, Length - 30 mm, Round radius - 2 mm

The gap between cylindrical electrode and the work piece was set to 0.64 mm. For this value, a feed speed of tool electrode corresponded to 1 mm/min. Other input data needed for the simulation were:

- Node number – 20, Total processing time – 30 min, Time increment Δt - 0.5 min

The result of the simulation is presented in figure 8 for a processing depth equal to 25 mm. In figure 9 it is possible to observe a detail of the work-piece obtained for a depth feed of Z=15mm. In this detail it can be seen how the side gap increases, an effect observed in reality.

Conical tool-electrode

The conical tool-electrode used in simulation has following dimensions:

- Top radius – 30 mm, Cone angle - 25°, Length – 30 mm, Round radius – 0.5 mm

The size of gap between the conic electrode and work-piece had a value of 0.42 mm. For this value, a corresponding feed speed of tool electrode equal with 1.5 mm/min is used. The other input data needed to run the simulation was identical with those from the simulation of the cylindrical electrode.

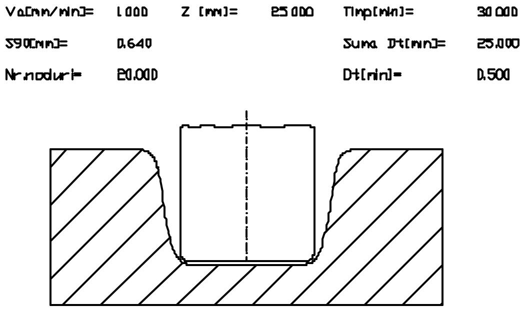

Fig. 8

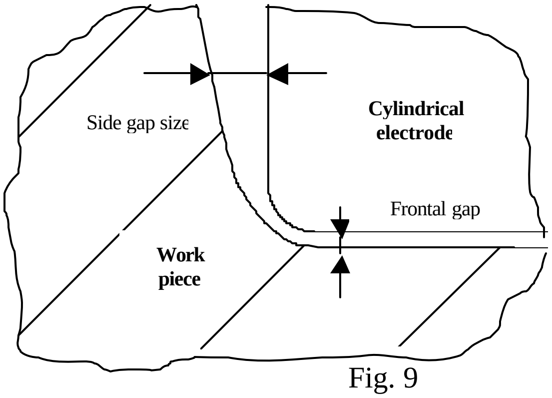

Fig. 9

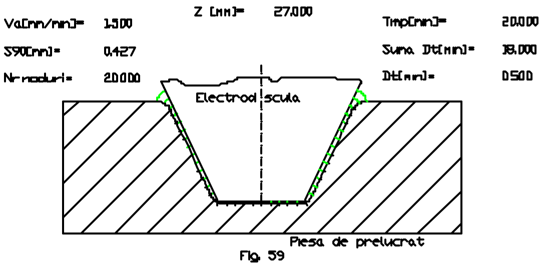

Fig. 10

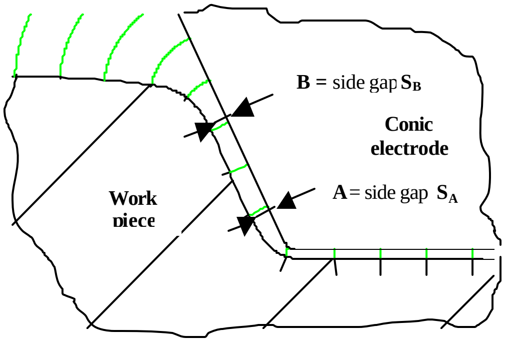

Fig. 11

The evolution of the simulation is presented in figure 10. A detail of the work-piece shape at z=9mm erosion depth is given in figure 11. In this detail it can be seen that a side gap S_A approximately equal with side gap S_B. This behaviour was confirmed in real processing and thus validates once again the simulation program developed.

Spherical tool-electrode

A spherical shape is considered representative for processing complex surfaces by electrochemical erosion. Also, using a spherical shape, a complete verification of the simulation program was possible, because this shape covers regions with angles greater than 60° where "cosines" law cannot be used for the gap determination. Before displaying the graphical simulation window, the following input data is requested:

- The position of the tool electrode centre (the default value is <400,500> and user can accept or change it)
- Tool-electrode radius (default value <30> mm)

The simulation parameters needed:

- Feed speed of tool-electrode – 0.5 mm/min, Nodes number used - 40 nodes, Total processing time – 60 min, Time interval Δt - 0.5 min (this value is connected with tool feed speed in such a way so that a total depth of erosion 30 mm is achieved, which is equal to the tool radius)

This input data and the value for frontal gap size, Y_f = 1.281 mm is displayed in a graphical window for monitoring purposes. The result obtained from this simulation, using a spherical tool-electrode, is presented in figure 12. The final stage is in accordance with erosion depth at the end of process and the shape of the work-piece at that time. The initial work-piece is assimilated in simulation process with a box with the height 5-10 mm bigger than maximum erosion depth. The basic electrochemical data used for this simulation are stored in a database connected with simulation procedure. Values extracted from this database are:

- Effective volume of removed material - 2.44 mm3/Amin, Electrolyte conductivity (NaCl solution)– 0.0164 s/mm, Polarisation voltage drop – 2V, Applied voltage – 18V

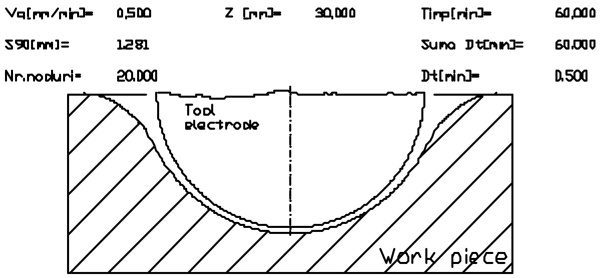

Fig. 12

Fig. 13

RESULTS

The simulation results were compared with real part profiles for each shape presented cylindrical, conical and spherical. The error measured along the contour of the profile was not bigger than 0.15 mm that confirm this simulation program as an good instrument in evaluating the shape of work piece for a given tool electrode. The three parts measured are presented in next figure 13, 14, and 15.

Fig. 14

Fig. 15

FURTHER WORK

As can be seen from figure 13, the geometrical shape obtained after processing with a spherical electrode is not good enough from a geometrical and dimensional point of view. The main phenomenon observed is an increasing of gap size between the two electrodes through the tool contour and normal to this contour. This increase resulted in a different work-piece geometry from that desired – a spherical shape. In order to eliminate this phenomenon and thus to increase dimensional and geometrical accuracy in electrochemical process it was possible to extend the simulation to a new stage. This consisted of designing tool electrodes for ECM machines using this simulation in order to obtain an accurate work-piece profile by appropriately shaping the electrode. The outcome of this part of the work has been presented elsewhere [11].

REFERENCES

1. Kawafune, K., Mikoshiba, T., Neto, K. “Einflus der Einstellbedingungen auf den Bearbeitungspalt beim elektrochemischen Abtragen”. CIRP-ANN.18, 1970, 2, s.305.
2. Alekseev, G. a. “Kathoden oberflachenprofil bei der elektrochemischen Bearbeitung”. Stanki I Instrument 41, 1970.3.
3. Dietz, H., Gunther, K.G., Otto, K., “Electrochemical Machining: Calculation of Size Gap with Respect to Hydrogen Evolution”. Annals of the CIRP, Vol.23/1, 1974, p. 45-56.
4. Konig, W., and Humbs, H.H., “Mathematical Model for the Calculation of the Contour of the Anode in Electrochemical Machining”. Annals of the CIRP, 26/1, 1977, p. 83-86.
5. Tipton, H., “The Calculation of Tool Shapes for Electrochemical Machining”. Fundamentals of ECM. The Electrochemical Society, Princeton, 1971, p. 87-102.
6. Raju, K.R., Jain, V.K., Lal, G.K., “Cathode Design in ECM: Two Dimensional Analysis”. ASME Symposium on Research and Technological Advances in Non-traditional Machining. Vol. PED-34, 1988, p. 89-104.
7. Seimiya, K., “An Approximate Method for Predicting Gap Profiles in Electrochemical Machining”. Proceedings of the 5th International Conference on Production Engineering, 1984 p. 389-394.
8. Hewidy, M.S., Rajurkar, K.P. “Computer-Aided Tool Design in ECM”. Proc. of the Third Int'l. Conference on Computer-Aided Production Engineering, 1988, p. 371-380.
9. Jain, V.K., Rajurkar, K.P. “An integrated Approach for Tool Design in ECM”, Submitted for review to the Precision Engineering, May 1990.
10. L. Dabrowski and J. Kozak, Electrochemical Machining of Complex Shape Parts and holes (Mathematical modelling and practical experiments), Warsaw Technical University, Poland.
11. Temur R., Coole T., Bocking C., “ECM Tool-electrode Construction for Semi-spherical Shapes”, Research and Development in Net Shape Manufacturing, Birmingham UK, April 2001.