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MILITARY TECHNICAL COLLEGE

CAIRO - EGYPT

WORKPIECE SHAPE ERRORS IN ELECTROCHEMICAL MACHINING

A.M.Abdel Mahboud

Associate Professor, Faculty of Engineering
Menoufia University, SHEBIN EL KOM
EGYPT

ABSTRACT

Experimental and analytical investigations are conducted to determine the profile change along the frontal inter- electrode gap (IEG) in the course of electrochemical machining.The inter-electrode machining parameters are described mathematically in the steady state condition and a computer program is developed to solve the obtained formulae. A comparison between theoretical and experimental results are also carried out. A discussion of certain limitations to the ECM process is presented.

INTRODUCTION

The process of ECM dissolution in ideal conditions obeys Faraday's and Ohm's laws. In practical conditions, however, this is violated because the laws do not account for the number of important parameters, such as, hydrodynamic conditions of the electrolytes and there chemical and physical properties ..etc, which in total determine the exact conditions of the ECM process. Also, the size of the IEG depends not only on the machining parameters, but also on the local conditions occurring in the vicinity of the point considered. Therefore, the main problems of the ECM process description are not the determination of the parameters across electrolyte flow, but also their distribution over the electrode surface.

The objective of this paper is to describe the variation in the process parameters along the electrode surface. Also, to study there effect on the resulting profile under steady state conditions.

PROCESS DESCRIPTION AND PRODUCED SHAPES

To describe an ECM process and hence, the resultant shapes, it is necessary to solve a set of transport equations of charge, mass, energy, and motion for an area with moving boundary. Due to the high complexity of such tasks, approximate methods of solution were employed, of which the most frequently used is the one dimensional description method.
Two main categories for workpiece shape prediction could be described, namely the frontal process and the side-frontal

one.Regarding machining with both frontal and side gap. some models have been developed in one dimension gap model [1-4]and in 2D gap model[5-6].
In this study machining with frontal gap only is considered. Tiption [7] neglected void fraction and studied the effect of temperature dependent electrolyte resistivity on the shape of electrode gap. Kawafune et. al. [8]. on the otherhand, neglected temperature effects and studied the effect of void fraction and gas compressibility in 2D gap model. Thorpe and Zerkle [9] defined a comprehensive analytical basis on the dynamic of ECM and carried out an order of magnitude analysis which showed that void fraction and temperature effects are of the same order of magnitude. This work also resulted in the definition of a quasi - static ECM process [10]. Furthermore, in another paper [11] they considered a general problem of predicting equilibrium gap profile and developed a set of equations [12 - 13] and solved them numerically to yield one dimensional distribution of the process parameters along the IEG. Due to the complexity of the problem they assumed that the cathodic hydrogen gas bubbles are uniformly distributed throughout the gap. Nonetheless, that assumption is in contrast to experimental observations, made by Landolt et. al. [14], that hydrogen gas bubbles form a layer next to the cathodic surface whose thickness increases in the electrolyte flow direction. Hopenfeld and Cole [15] considered a quasi-static ECM process in which temperature effects were ignored and the effect of void fraction on current density was determined. In another paper [16] they considered a general problem of the equilibrium process. Upon comparing the predicting gaps with corresponding experimental data, they found good qualitative agreement. Loutrel and Cook [17-18] developed a model taking into account the multiphase flow of electrolyte. They used a simplified form of the Navier Stokes equations for predicting the gap profile. Because of inaccurate determination of the system of input and output boundary conditions considerable deviations have been noticed in the results. Mc.Geough and Stronach [19] presented an experimental procedure for measuring pressure distribution in the IEG. A modified theoretical model for the parameters variation throughout the gap was also developed. A one dimensional two phase flow theory was formulated by Rousar [20] for the electrolyte gas mixture behaviour in the IEG. The condition for generating the choked two phase flow is described and the initiation of choked two phase flow is also discussed.

A review of the previous work showed that the previous analytical solutions are available for predicting the equilibrium gap if certain unwarranted assumptions are made. On the other hand, it would appear that a computer solution is necessary, if realistic results are desired, but having an available computer program does not necessarily provide insight into the ECM process. Moreover , the problem of mass transport throughout the diffusion layer and the anodic and cathodic potential variations are not included. However, Petrov et. al. [21] formulated a set of equations to solve the problem of mass

transport in diffusion layer. Their results showed that the metal output distributions measured in tests differed from the calculated values and such distributions are typical for diffusional constraints of the dissolution process and are defined by the diffusicn current distribution law.

EXPERIMENTAL WORK

Experiments were carried out using an electrochemical machine shown schematically in Fig.1.which was designed and developed in IMT,ZOWE.Warsaw Technical University Poland. The machining cell consists of rectangular flow channel. Its side walls were made of flat perspex plates. The design of flow channel provided for fully developed electrolyte velocity profile at the electrode [22].Fig.2.shows the layout of the machining cell and measuring points.Test specimens were made from Armco iron. Brass material was used as a cathodic material. Tool and workpiece are made with an initially plane parallel electrode of length 55 mm in the flow direction and breadth of 15 mm. The side leakage of the electrolyte was avoided and the flow was contained within the tool workpiece area. Each test specimen was ground and mechanically polished. Sodium Nitrate solution (10% w/v) was used for the electrolyte solution.

Five pressure taps were made in some specimens to measure the pressure distribution along the gap. Moreover, the inlet pressure was held at a constant value for each test run and the back pressure was atmospheric.Machining was conducted until the steady state was achieved The machined profiles were measured using a dial gauge (0.01mm accuracy)and readings were taken at intervals of 5 mm. Also, the surface roughness was measured at equal intervals of 5 mm .

MATHEMATICAL MODEL

The main task of the mathematical modelling is to determine the shape of machined surface by preset tool shape under known machining conditions,especially when machining with flat electrode or cylindrical tool having great radius of curvature. The analytical model used in this study, which was previously derived by the authors in Refs.[23,24], is illustrated in Appendix 1.This model was solved numerically using Rung-Kutta method on a PC.
The following procedure was used to solve the system of equations(6-13) obtained using successive approximations method.

1-The electrode surface is divided by nodal points into finite number of sections.

$$0 < x_1 < x_2 < x_{i-1} < x_L$$

For simplification purposes the constant length of integration step my be presumed to be $h = L / N$ and $x = ih$ ($i = 0.1.2...N$) where N - number of sections.
2-Assuming that $\beta=0$. $T=To$ and $\Delta U=\Delta Uo$ and solved numerically

equation (6).This yields the first approximation of inter-electrode gap width S distribution.
3-Combining equations (9-10)and integrated them numerically ,we obtain the values of W_o,P which in this iterative cycle constitute the first approximation of hydraulic parameters.
4-We solve in numerical way equations (11-13) acquiring the first approximation of β.T distribution.
5-We calculate the first approximation of current density on the basis of relation (8).
6- we determine new value of ΔU utilizing the known basic characteristics of ECM.dissolution.
7-We repeat the calculation cycle starting with numerical solution of equation (8) applying variable values of β.T.k ΔU along x.
The iterations are repeated until the assumed accuracies are obtained and the program is stop at

$$Tmax < T1$$
$$Ma=W/C < 1$$

where Ma is Mach number and equal to

$$Ma(i)=W(i)/[\ P(i)\ /\ 2.5\beta(i)(1-\beta(i)\rho_e]$$

C is the local speed of sound and T1 is limiting temperature which must not be exceeded

RESULTS AND DISCUSSION

Fig.3. shows an example of the results obtained from the above analytical model.The results shown in Fig.3 agree with the results obtained by Kozak et. al. [25]. However, under certain conditions (as high feed rate) sonic velocities are attainable near the gap exit (Ma≥1)due to the compressibility of the gas bubbles.Moreover,by knowing the distribution of gap S(L) on can determine the shape of machined surfaces and conduct the analysis of machining accuracy.Also, by modifying the program one can find out the shape of electrode for the required machined surface.

In order to confirm the adequacy of the proposed model, a wide range of experimental tests were performed and shown in Figs.4-7.
Figs.4-7,show the effect of the machining parameters on the gap profile. It was evident that the gap tapers in a divergent fashion along most of the electrode length, only becoming convergent towards the outlet of the flow direction. That is, Joule heating has predominated over the presence of hydrogen bubbles, thereby increasing the effective conductivity of the electrolyte. The lower the flow rate the further upstream occurs the location of change over from a divergent to convergent gap. This effect may arise with an increase in diameter of the hydrogen bubbles at lower flow rate. The associated increase in the specific volume of hydrogen bubbles in the gap means that the gas yields a greater influence in reducing the effective conductivity of the solution. The latter effect still takes place towards the gap outlet. because only

in that region the local pressure is apparently low enough to allow sufficient increase in the bubble diameter and in the specific volume of the gas.

Fig.8,shows the roughness distribution along the electrode in the flow direction. It could be noticed that the Ra value increases along the electrode length. That trend is consistent with the hypothesis that the hydrogen bubbles forming on the cathode surface might act as small protrusions which increase the relative effective roughness and hence the friction factor. Moreover, as the feed rate increases the flow rate may be reduced. Hence, at lower electrolyte flow velocity, an increase in bubble diameter was noticed [14,22] and the greater roughness along the electrode length. With zero current applied, the pressure was uniquely determined by the electrolyte mass flow rate and the gap size between electrodes. With the current on the inlet pressure and hence, the pressure distribution was affected by the intensity of the current passed between the electrodes (Fig.9).

Moreover,the effect of change in the inlet pressure on the profile error is shown in Fig.7.It can be seen that the change of inlet pressure affects the relative change in the profile shape.This was to be expected, as mentioned before, because of the comparatively higher compressibility of the mixture at lower flow rates. Also, since the pressure is proportional to the square of the electrolyte velocity slight changes in the gap value and hence electrolyte velocity, influence the value of local pressure and as these changes accumulate along the gap so a significant error can occur. The accuracy and surface roughness and profile straightness are improved as the result of increasing feed rate.But high feed rate conduct into short circuit and electrodes damage. Furthermore, high feed rate causes the choking effect at the electrode exit, which eventually heightens the profile errors and disturbs the ECM process. Moreover, the breakdown of the profile may be attributed to a valency change along the electrode length. The switch from one valency to another during machining is sensitive to conditions of feed rate and flow rate [26].

Finally,a fair agreement between analytical and experimental results are noticed in Fig.10.So, it could be stated that the gap size will exceed equilibrium value when heat building up is predominant, and it will be smaller than equilibrium value when the gas content has a greater effect. The general effect of void fraction can be reduced by increasing the back pressure to a level substantially above atmospheric. Also, the determination of the local gap value depends on the interaction between local pressure, void fraction and Joule heating equations all of which are influenced by upstream conditions, although the pressure is also influenced by downstream conditions.

CONCLUSIONS

The analytical and experimental results described in this paper appear to give reasonable description of the profile change during ECM under steady state conditions. High electrode feed rate causes the choking effect at the electrode exit, which eventually heightens the gap shape error and disturbs the process.Moreover , the results indicate that the gap size will exceed the equilibrium value when heat building up is predominant.while it will be smaller than the equilibrium value when the gas contents has a greater effect.

ACKNOWLEDGEMENT

The author acknowledges with thanks the staff members of Warsaw Technical University, IMT, ZOWE for their help in carrying out this work.

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NOMENCLATURE

E	Applied voltage (V)
VF	Tool feed rate (mm/min)
SO	Initial gap width (mm)

W Electrolyte flow velocity (m/s)
Pin Inlet pressure (MPa)
Po Outlet pressure (MPa)
S Inter electrode gap thickness (mm)

APPENDIX

FUNDAMENTAL EQUATIONS OF THE MATHEMATICAL MODELLING

In this model it can be considered that the electrode have a flat surface or cylindrical having a great radius of curvature.The geometry of the model is illustrated in Fig.(A-1).On the basis of the accepted assumption on can elaborated the following system of equations.
The specific density of the two phase medium is

$$\rho=\rho_e(1-\beta)+\rho_g\beta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where ρ, ρ_e are electrolyte and gas densities
β gas concentration volume

The conductivity of the two phase medium is

$$\varkappa=\varkappa_o(1+\alpha\Delta T)(1-\beta)^{1.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where α temperature coefficient of condctivity

$\varkappa_o$ electrolyte conductivity at T=To ,β=0

The absolute viscosity of the two phase medium is

$$\mu=\mu_o(1+m\beta)e^{-b(T-T_o)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where m and b are constants m=5.5 ,b=.019

Pressure losses on a distance dx of the gap is

$$dp/dx = -0.316\,\rho\,W^2/4\,Re^{0.25}\,S \quad \ldots\ldots\ldots\ldots(4)$$

where $Re = 2SW\rho/\mu$

The variability of current efficiency η for mild steel in 10 % NaNO3 is determined in empirical form [A-1,A-2]

$$\eta=f(j,T)=\exp(29.07-6.71nT-.04(lnj)^2+0.208lnjlnT)\ldots\ldots(5)$$

CORRELATION OF ELECTRODES IN STEAD STATE CONDITION

The local gap width is

$$S(i)=S(1)\eta(i)\varkappa(i)[E-\Delta U(i)]/\eta(1)\varkappa(1)[E-\Delta U(1)]\ldots\ldots\ldots(6)$$

where $S(1)=\eta_1 KE\varkappa_1/\rho\,VF$ .....(7)

The local anode current density is as follows

$$j(i)=\varkappa(i)[E-\Delta U(i)]/S(i) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

The equation of continuity has the following form

$$W(i)S(i)[1-\beta(i)]\rho_e = \text{const} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Pressure distribution in the gap is as follows

$$dp/dx = -\frac{0.067\,\nu^{.25}\,W^{1.75}\,(1+m\beta)^{.25}\,\rho_e\,e^{-.019(T-To)}}{S^{1.25}} \quad \ldots\ldots (10)$$

where ν is the kinematic viscosity

Temperature distribution is provided by

$$dT/dx = j^2(i) \,/\, \varkappa(i)\,\rho_e W(i)\,S(i)\,[1-\beta(i)]Cp \quad \ldots\ldots\ldots (11)$$

where Cp is the specific heat of electrolyte

Distribution of mass concentration of hydrogen is given by

$$d(\beta_m WS)/dx = \eta\, k_H j_H \quad ,\beta(x_m=0) = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

and the volumetric gas concentration is

$$\beta = T\,10^5\,\beta_m \,/\, 237\,P\,\rho_H \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

where ρ_H is the hydrogen density at $P=10^5 N/m^2$ and $T = 237$ k.

η_H .K_H are current efficiency and electrochemical equivalent of hydrogen respectively.

The above system of equations (6-13) should be solved under the following boundary conditions

for i=1 P(i)=Pin ,T(i)=Tin ,$\beta(i)=0$,$\varkappa(i)=\varkappa o$

for i=n P(i) =Po

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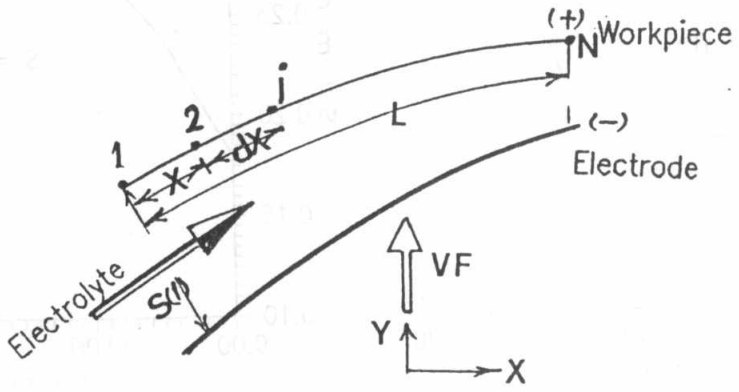


Fig.(A-1) Geometry of the IEG model

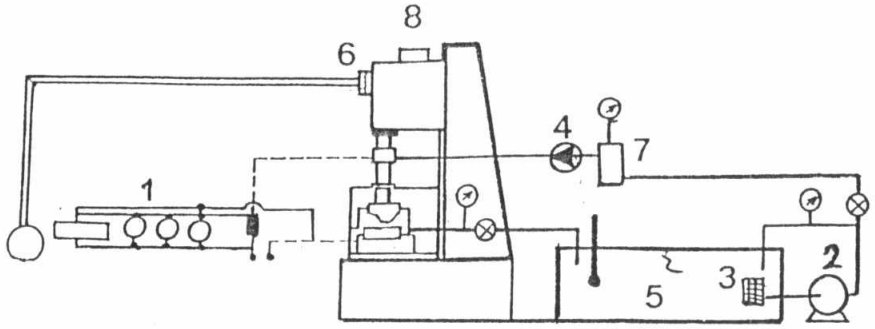


Fig.(1) Layout of ECM machine
1-power supply 2-pump 3-filter 4-valves 5-electrolyte tank
6-displacement transducer 7-electrolyte gas mixing chamber
8-hydrulic motor

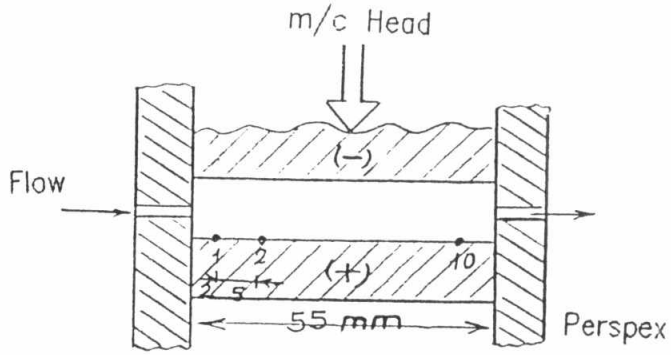


Fig.(2) Schematic layout of machining cell and measuring points

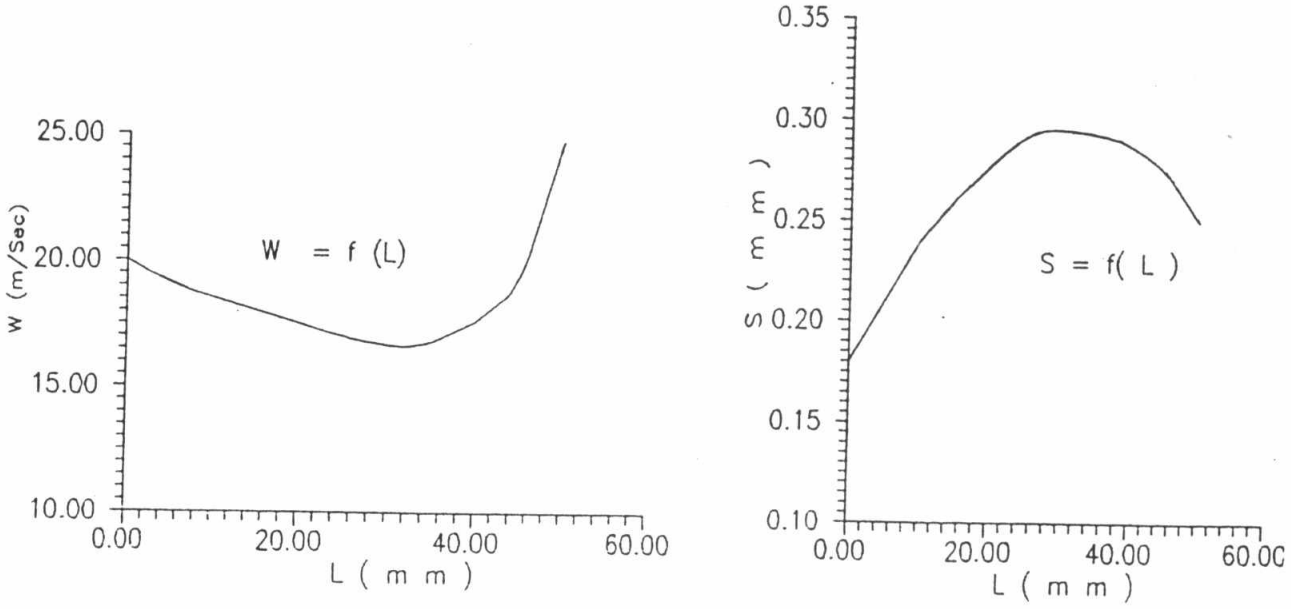
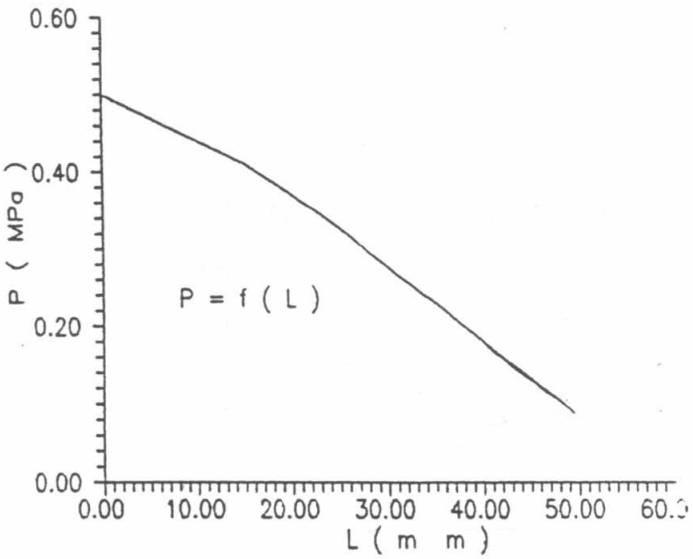
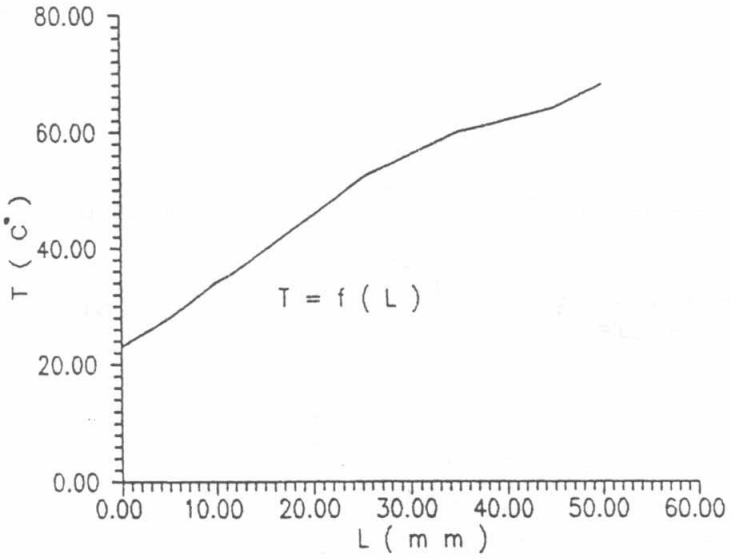
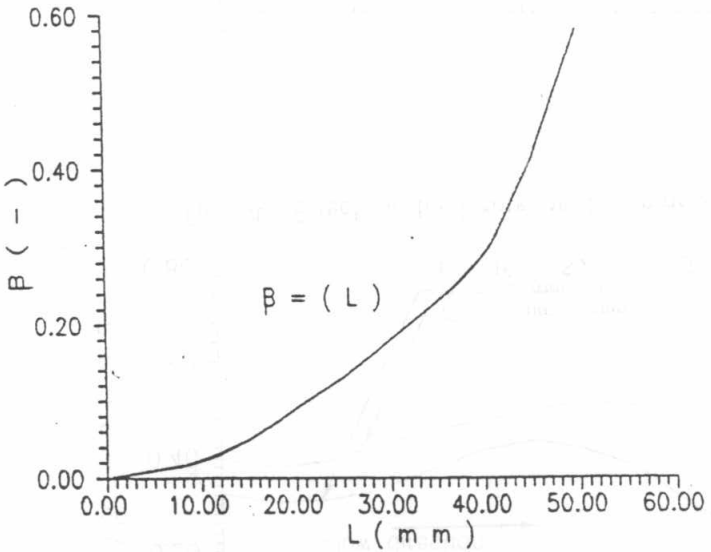


Fig.(3) Distribution of ECM variables along electrode length
VF=2 mm/min ,Po= .1MPa ,15 % NaNo3 ,SO= .3 mm







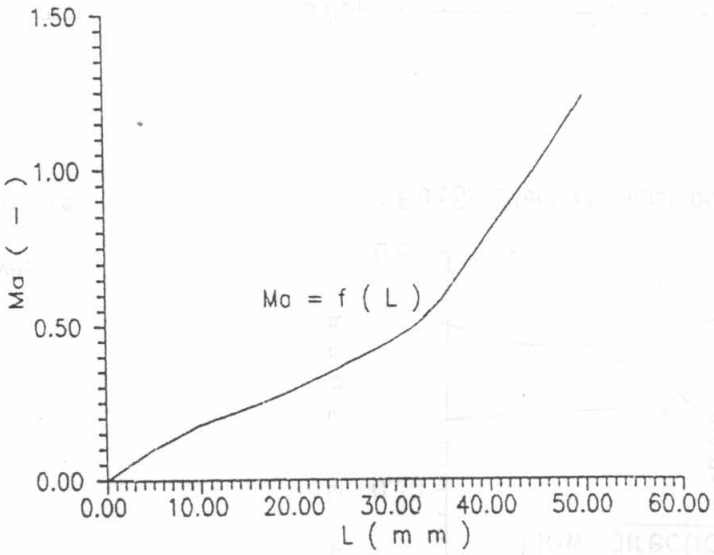


Fig.(3) Cont. Distribution of ECM variables along the electrode length
VF=2mm/min ,Po=.1MPa,15 %NaNo3 ,SO=.3 mm

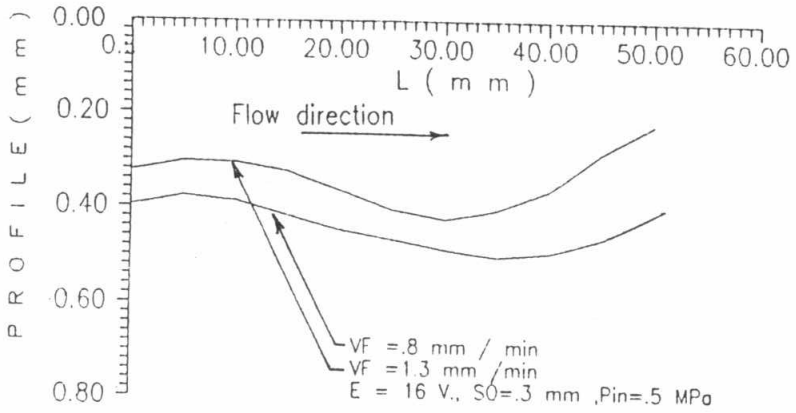


Fig.(4) Effect of feed rate on the machined profile

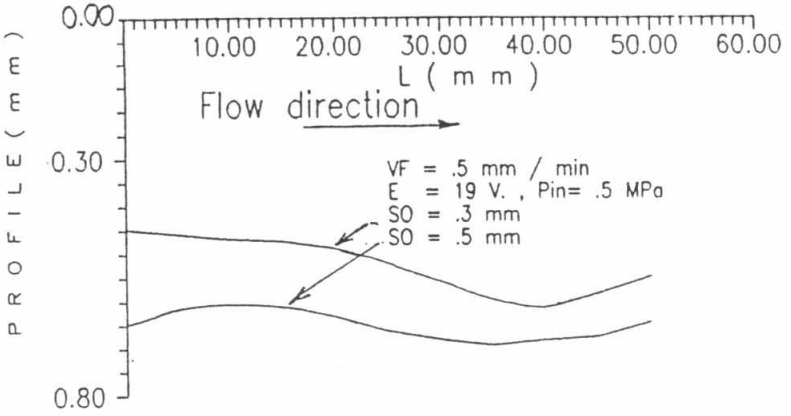


Fig.(5) Effect of initial gap width on the machined profile

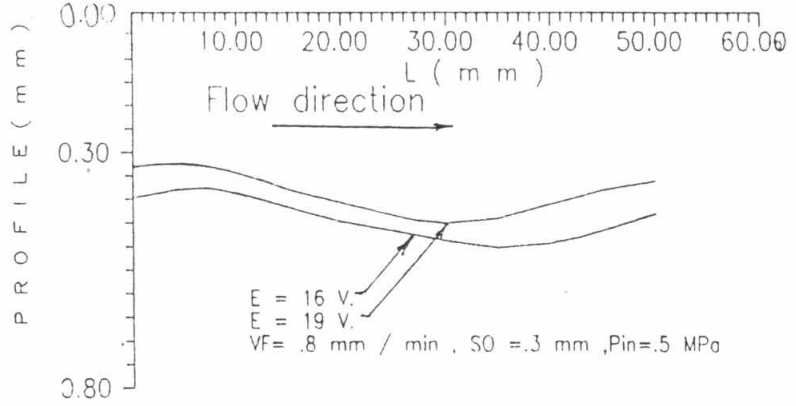


Fig.(6) Effect of applied voltage on the machined profile

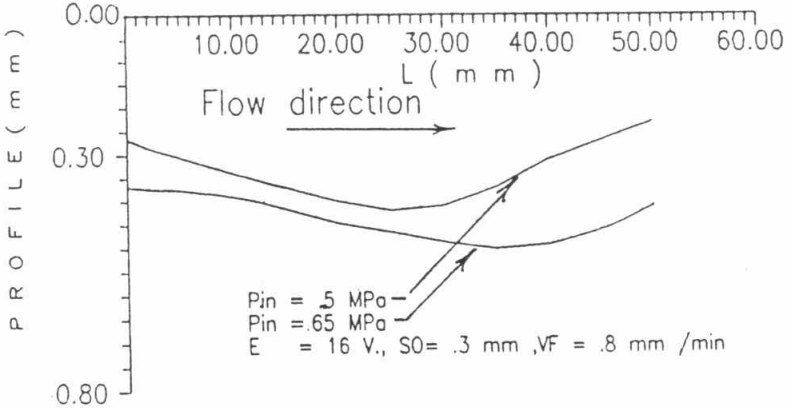


Fig.(7) Effect of inlet pressure on the machined profile

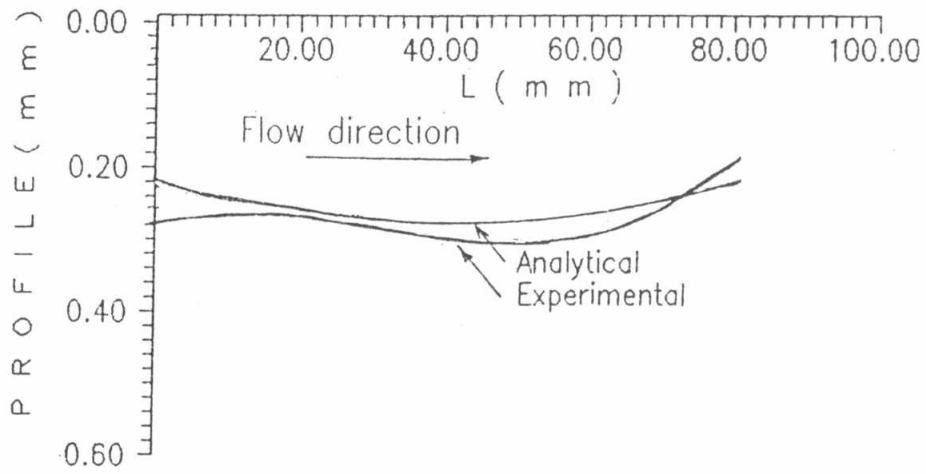


Fig.(10) Comparison between analytical and experimental gap profile
VF=.7 mm/min ,E=16 V.,Pin=.7MPa,10 %NaNo3 , ΔU=2.5 V.
$\eta_H = 0.25$

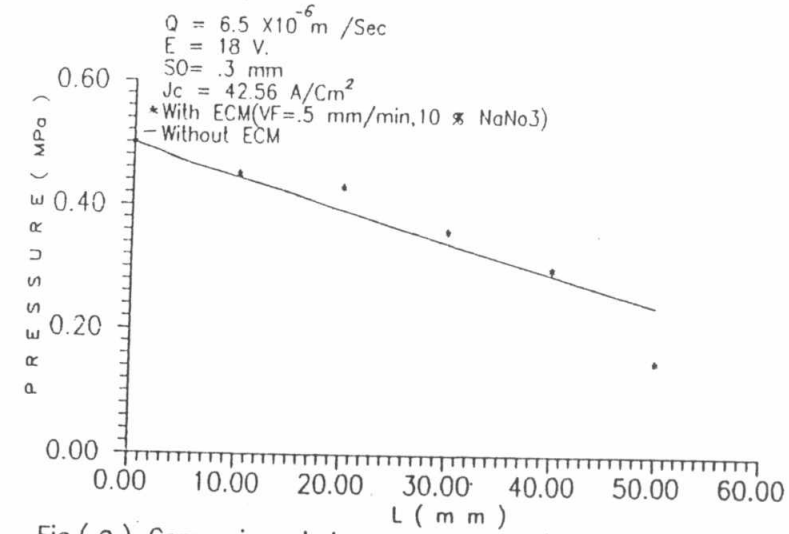


Fig.(9) Comparison between pressure distribution along electrode length with and without ECM

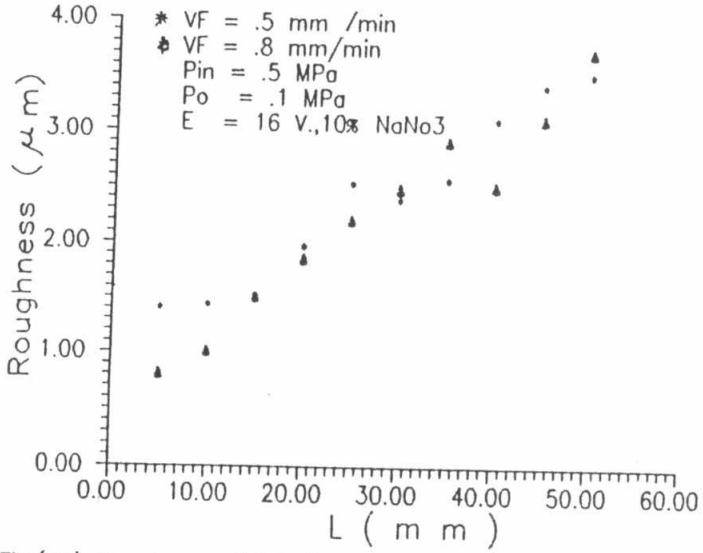


Fig.(8) Roughness distribution along the electrode length