Modeling and Simulation of the Dimensional Accuracy in the ECM Process

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Abstract

Electrochemical Machining (ECM) has found wide applications in aerospace, automobile, nuclear and similar other industries. However, from the manufacturer point of view, ECM is still a random process which delays the use of this technology. This paper submits theoretical models and computer simulation to solve problem of the dimensional accuracy in the ECM process. In the present work, dimensional accuracy has been investigated through the computation of the standard deviation of workpiece dimensions which has not been considered before. A special test rig has been established to confine with the features of this process. It is, however, felt that the capacities of the process have not been fully exploited, due to the difficulties encountered in the prediction of the ECM accuracy. This problem delays the use of this process. The results show that standard deviation is a promising factor towards an accurate prediction of the dimensional accuracy of the ECM process.

1 . Introduction

Non-traditional machining processes, particularly electrochemical machining (ECM), offer the unique advantages of a better accuracy and a high surface integrity of the machined components [1]. In the ECM process metal removal takes place when a voltage is applied between two metal electrodes that are immersed in an electrolyte. "ions," electrically charged groups of atoms, migrate physically through the electrolyte and in doing so carry the current. The transfer of electrons between the ions and electrodes completes the electrical circuit and also brings about the phenomenon of metal dissolution at the positive electrode, or "anode" which is the workpiece [2-3].

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The process was developed primarily to machine advanced aerospace materials for complex shapes. Recent applications of the ECM process have been used in operations similar to cavity sinking, broaching, trepanning, contouring, drilling, smoothing, deburring, turning, shaping, grinding and micromachining of complex surface geometry and difficult-to-machine contours irrespective of material shear strength, hardness etc. ECM is now used in areas such as aerospace, automotive, nuclear, surgical implant components, computer parts, forging dies, etc., for fast production with high quality of surface integrity than other machining processes [4-7].

It is, however, felt that the capabilities of the process have not been fully exploited, due to the difficulties encountered in the prediction of ECM accuracy [4]. This problem delays the use of this process. The accuracy of the ECM process should be considered from several angles: compliance of the finished part with its drawing in terms of shape and dimensions; transfer of tool shape to the workpiece; and repeatability of dimensions in parts taken from a sufficiently large lot machined with the same tool electrode. In electrochemical die sinking the primary objective is to maintain the form tolerance as closely as practicable [7]. To achieve this, it is essential to use a tool of the right form and size and the right process parameters. This requires for the design of a suitable tool and, in consequence, the computation of the form and dimensions of the finished part that will be produced by a given tool. All of this can be achieved only from the analysis of ECM accuracy [7].

Many papers concerning the accuracy in the ECM [8-14] process have been published. The concept of the standard deviation has been submitted in ECM to study roughness and gap size [15-17]. However, it has not been submitted before to consider the dimensional accuracy.

The objectives of this investigation are to: 1) develop the theoretical models of the standard deviation of the dimension of the workpiece in the ECM process; 2) perform computer simulation concerning the standard deviation of workpiece dimension; 3) analyze the influence of the process parameters occurring within the machining area on standard deviation of workpiece dimension; and 4) design and carry out the experiments to verify validity of the developed theoretical models.

2 . Modeling of the Dimensional Accuracy

In the manufacturing process, it has been reported that the dimensional accuracy depends on the natural tolerance which is $\pm 3\sigma_B$ [18], where σ_B is the standard deviation of the dimension of the workpiece. The standard deviation of the dimension of workpiece σ_B is affected by a number of parameters such as, cathode feed rate V_f, electrolyte conductivity χ, volumetric electrochemical equivalent K_v, applied voltage , gap size S, initial gap size S_0, initial workpiece dimension A, and their standard deviations σ_{V_f}, σ_χ, σ_{K_v}, σ_U, σ_S, σ_{S_0}, σ_A

respectively. It is essential to find the functional standard deviation of workpiece σ_B to establish the influence of the process parameters as well as those phenomena occurring within the machining area.

To develop the models of the dimensional accuracy the following assumptions are presumed: (1) Ohm's law holds over the entire gap up to the surfaces of the electrodes; (2) the electric conductivity of the electrolyte in the gap remains constant in both time and space; (3) at each electrode, the potential remains the same over the entire surface area and throughout the machining time; (4) current efficiency for the anodic dissolution of the metal is the same at any point on the surface of the workpiece; (5) no heat transfer through the interelectrode gap is considered.

The general procedure to develop the models of the dimensional accuracy are, first, the function of the dimension B, which is related to the geometric parameters of the workpiece and the process parameters mentioned above, has to be found. Then, by using the tolerance transfer law [19] along with the anodic dissolution relation and the gap size equation the standard deviation of the dimension B of the workpiece can be developed. In this section, the models of the dimensional accuracy consider both namely; with no feed rate and with feed rate.

2.1 Models of the Dimensional Accuracy under ECM stationary Tool Conditions

A stationary tool (no feed rate case) is often used in finishing operations [4,5,6,7]. It is therefore important to know how the macro irregularities originally present on the surface of the workpiece vary with the progress of the ECM process. In the ECM process the configuration of stationary electrode tool and workpiece is shown in Fig. 1. Two models are developed.

A) Model for given initial gap size S_0 and machining time t_m

From Fig. 1, the geometrical relations of the initial gap size and the dimension B of the workpiece can be found as follows :

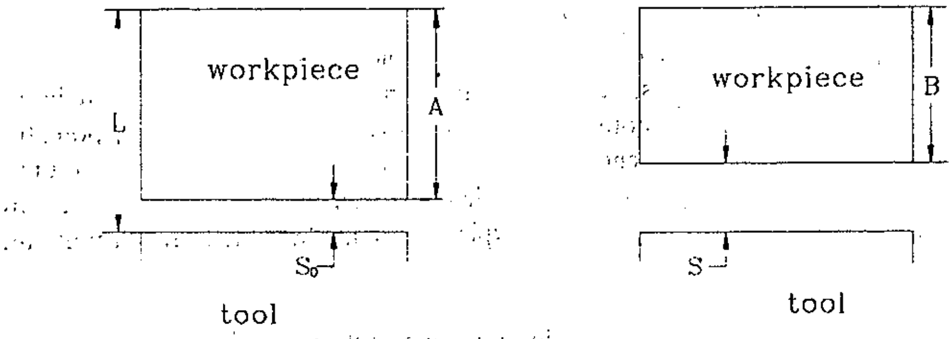
$$S_0 = L - A, \tag{1}$$

$$B = L - S. \tag{2}$$

For feed rate $_f = 0$, from Faraday's law and Ohm's law the anodic dissolution can be written in the form of [6]

$$\frac{dS}{dt} = \frac{\chi K_v U}{S} \tag{3}$$

where χ is the electrolyte conductivity (A/v.mm), K_v is the volumetric electrochemical equivalent of the anodic material (mm^3/A.min), U is applied voltage (volts), S is the gap size (mm), t_m is the machining time (min), S_0 is initial gap size (mm). By integrating the Eq. (3) from $t=0$ to $t=t_m$, the gap size is then obtained in the form of :



(a) Before machining (b) After machining

Figure 1. Workpiece and tool dimensions in the ECM process

$$S=\sqrt{S_0^2+2\chi K_v U t_m} \tag{4}$$

Substituting Eq. (4) and Eq. (1) into Eq. (2), the function of the dimension B will be equal to :

$$B=S_0+A-\sqrt{S_0^2+2\chi K_v U t_m} \tag{5}$$

Gellert et al. [19] have described the tolerance transfer law as: the variance σ_y^2 is a sum of the products the variances of the noise factors, $\sigma_{x_i}^2$, and the sensitivity coefficients, $(\partial f/\partial x_i)^2$. By using the tolerance transfer law [19] the standard deviation of the dimension B can be expressed in the next form. The general formula which has been suggested to represent σ_B in the manufacturing process has been adapted to confine with all the parameters.

$$\sigma_B=\left[\left(\frac{\partial B}{\partial A}\right)^2\sigma_A^2+\left(\frac{\partial B}{\partial S_0}\right)^2\sigma_{S_0}^2+\left(\frac{\partial B}{\partial \chi}\right)^2\sigma_\chi^2+\left(\frac{\partial B}{\partial K_v}\right)^2\sigma_{K_v}^2+\left(\frac{\partial B}{\partial U}\right)^2\sigma_U^2+\left(\frac{\partial B}{\partial t_m}\right)^2\sigma_{t_m}^2\right]^{\frac{1}{2}} \tag{6}$$

where $\sigma_A, \sigma_B, \sigma_{S_0}, \sigma_\chi, \sigma_{K_v}, \sigma_U, \sigma_{t_m}$ are the standard deviations of A, B, S_0, χ, K_v, U, t_m, respectively. Therefore, by using Eq. (5) along with Eq. (6) the standard deviation of the dimension B can be finally derived in the form of :

$$\sigma_B = \left[\sigma_A^2 + \left(1 - \frac{S_0}{\sqrt{S_0^2 + 2\chi K_v U t_m}} \right)^2 \sigma_{S_0}^2 + \frac{(\chi K_v U t_m)^2}{S_0^2 + 2\chi K_v U t_m} \left(\frac{\sigma_\chi^2}{\chi^2} + \frac{\sigma_{K_v}^2}{K_v^2} + \frac{\sigma_u^2}{U^2} + \frac{\sigma_{t_m}^2}{t_m^2} \right) \right]^{\frac{1}{2}} . \tag{7}$$

By using Eq. (7), the dimensional accuracy of workpecies in this case can be simulated, and controlled.

B) Model for given machining time t_m, distance L, and initial dimension A

Substituting Eq.(1) into Eq.(4), yields :

$$S = \sqrt{(L-A)^2 + 2\chi K_v U t_m} . \tag{8}$$

Substituting Eq.(8) into Eq.(2), we get :

$$B = L - \sqrt{(L-A)^2 + 2\chi K_v U t_m} . \tag{9}$$

Similarly, by using the tolerance transfer law the standard deviation of dimension B can then be derived as :

$$\sigma_B = \left\{ \frac{1}{(L-A)^2 + 2\chi K_v U t_m} \left[\left(\sqrt{(L-A)^2 + 2\chi K_v U t_m} - L + A \right)^2 \sigma_L^2 + (L-A)^2 \sigma_A^2 + (\chi K_v U t_m)^2 \left(\frac{\sigma_\chi^2}{\chi^2} + \frac{\sigma_{K_v}^2}{K_v^2} + \frac{\sigma_U^2}{U^2} + \frac{\sigma_{t_m}^2}{t_m^2} \right) \right] \right\}^{\frac{1}{2}} . \tag{10}$$

2.2 Models of the Dimensional Accuracy with Feed Rate

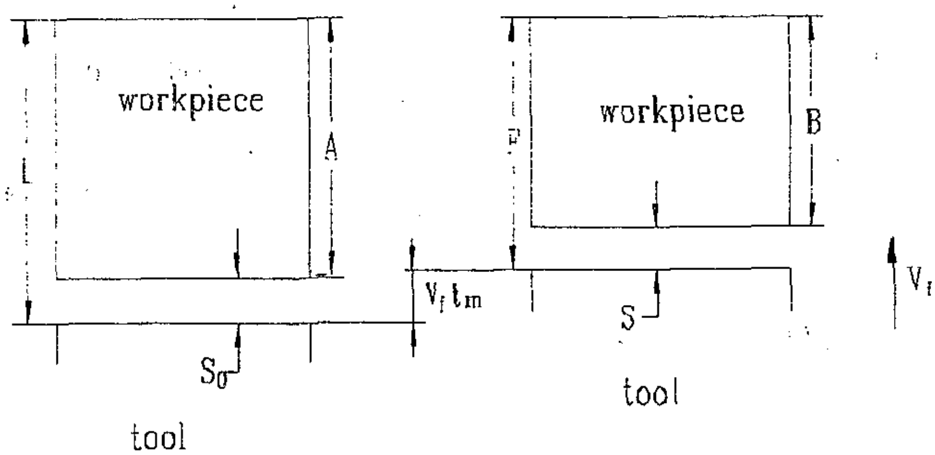
In practice, the ECM process with feed rate is widely used [4,5,6,7]. In this case the gap size varies with machining time in two states, i.e., transient state and steady state. The configuration of tool and workpiece dimensions under feed rate can be represented as shown in Fig.2.

The gap size equation (for $V_f \neq 0$) is [7]

$$(S_0 - S) - S_f \ln\left(\frac{S_f - S_0}{S_f - S} \right) - V_f t = 0, \tag{11}$$

where :

$S_f = \dfrac{\chi K_v U}{V_f}$ and $S_0 = L - A$.



(a) Before machining (b) After machining

Figure 2 . The configuration of workpiece and tool in the ECM process

A) Theoretical models for transient state

It is defined as the transient state before the gap size reaches the equilibrium gap. Here, the theoretical models of the dimensional accuracy will be developed under different input parameters.

(1) For given machining time t_m and initial gap size S_0

From Fig. 2.2 the geometric relationsships of the dimension B can be found from :

$$B = F - S, \tag{12}$$

$$F = L - V_f t_m, \tag{13}$$

$$L = A + S_0. \tag{14}$$

Substituting Eq. (13) and Eq. (14) into Eq. (12), yields :

$$B = A + S_0 - V_f t_m - S. \tag{15}$$

By using the tolerance transfer law along with Eq. (11), the standard deviation of the dimension B can be derived in the form of [20]

$$\sigma_B = \left\{ \sigma_A^2 + \sigma_{S_0}^2 + V_f \sigma_{t_m}^2 + t_m^2 \sigma_{V_f}^2 + \left(\frac{S_f - S}{S} \right)^2 \left[\left(\frac{V_f t_m + S - S_0}{S_f} + \right. \right. \right.$$

$$\left. + \frac{S_f (S_0 - S)}{(S_f - S_0)(S_f - S)} \right)^2 \left(\frac{\sigma_\chi^2}{\chi^2} + \frac{\sigma_{K_v}^2}{K_v^2} + \frac{\sigma_U^2}{U^2} + \frac{\sigma_{V_f}^2}{V_f^2} \right) S_f^2 +$$

$$\left. \left. V_f^2 \sigma_{t_m}^2 + \left(\frac{S_0}{S_f - S_0} \right)^2 \sigma_{S_0}^2 + t_m^2 \sigma_{V_f}^2 \right] \right\}^{\frac{1}{2}} . \qquad (16)$$

(2) For given machining time t_m and distance L

Substituting Eq.(13) into Eq.(12), yields :

$$B = L - V_f t_m - S \qquad (17)$$

By following the same previous procedure the standard deviation of the dimension B can be derived in the form of :

$$\sigma_B = \left\{ \sigma_L^2 + t_m^2 \sigma_{V_f}^2 + V_f^2 \sigma_{t_m}^2 + \left(\frac{S_f - S}{S} \right)^2 \left[\left(\frac{S_f t_m + S - L + A}{S_f} + \right. \right. \right.$$

$$\left. + \frac{S_f (L - A - S)}{(S_f - L + A)(S_f - S)} \right)^2 \left(\frac{\sigma_\chi^2}{\chi^2} + \frac{\sigma_{K_v}^2}{K_v^2} + \frac{\sigma_U^2}{U^2} + \frac{\sigma_{V_f}^2}{V_f^2} \right) S_f^2 +$$

$$\left. \left. + V_f^2 \sigma_{t_m}^2 + \left(\frac{L - A}{S_f - L + A} \right)^2 \left(\sigma_L^2 + \sigma_A^2 \right) + t_m^2 \sigma_{V_f}^2 \right] \right\}^{\frac{1}{2}} . \qquad (18)$$

(3) For given initial gap size So and distance F

By using Eq. (17) and the tolerance transfer law, the standard deviation of dimension B can be derived as

$$\sigma_B = \left\{ \sigma_F^2 + \left(\frac{S_f - S}{S} \right)^2 \cdot \left[\sigma_A^2 + \sigma_F^2 + \left(\ln \left(\frac{S_f - S_0}{S_f - S} \right) + \right. \right. \right.$$

$$\left. \left. \left. + \frac{S_f (S_0 - S)}{(S_f - S_0)(S_f - S)} \right)^2 \left(\frac{\sigma_\chi^2}{\chi^2} + \frac{\sigma_{K_v}^2}{K_v^2} + \frac{\sigma_U^2}{U^2} + \frac{\sigma_{V_f}^2}{V_f^2} \right) S_f^2 + \left(\frac{S_f}{S_f - S_0} \right)^2 \sigma_{S_0}^2 \right] \right\}^{\frac{1}{2}} \qquad (19)$$

(4) For given distances L and F

By using the tolerance transfer law and referring Eqs. (12) and (14), the standard deviation of the dimension B and initial gap size can be expressed as

$$\sigma_B = \left\{ \sigma_F^2 + \left(\frac{S_f - S}{S}\right)^2 \cdot \left[\sigma_A^2 + \sigma_F^2 + \left(\ln\left(\frac{S_f - L + A}{S_f - S}\right) + \right.\right.\right.$$

$$\left. + \frac{S_f (L - A - S)}{(S_f - L + A)(S_f - S)} \right)^2 \left(\frac{\sigma_\chi^2}{\chi^2} + \frac{\sigma_{K_v}^2}{K_v^2} + \right.$$

$$\left.\left.\left. \frac{\sigma_U^2}{U^2} + \frac{\sigma_{V_f}^2}{V_f^2} \right) S_f^2 + \left(\frac{S_f}{S_f - L + A} \right)^2 \left(\sigma_L^2 + \sigma_A^2 \right) \right] \right\}^{\frac{1}{2}} \quad .(20)$$

B) Theoretical models for steady state

It is defined as steady state in the ECM process when the gap size reaches equilibrium. Once the gap geometry is stabilized, for all practical purposes the part configuration is no longer changing because the work material at all points on the surface of the part is being dissolved at a rate equal to the tool feed rate. Theoretical models of the dimensional accuracy with different input parameters are presented as following:

(1) For given machining time t_m and initial gap size S_0

From Fig. 2 the geometric relation of dimensions can be written as :

$$B = A + S_0 - V_f t_m - S_f \quad (21)$$

By using the tolerance transfer law, the standard deviation of dimension B can be expressed as :

$$\sigma_B = \left[\sigma_A^2 + \sigma_{S_0}^2 + V_f^2 \sigma_{t_m}^2 + t_m^2 \sigma_{V_f}^2 + S_f^2 \left(\frac{\sigma_\chi^2}{\chi^2} + \frac{\sigma_{K_v}^2}{K_v^2} + \frac{\sigma_U^2}{U^2} + \frac{\sigma_{V_f}^2}{V_f^2} \right) \right]^{\frac{1}{2}} . \quad (22)$$

(2) For given machining time t_m and distance L

From Fig. 2 the geometric relation of dimensions can be written as :

$$B = L - V_f t_m - S_f \quad (23)$$

By using the tolerance transfer law, the standard derivation of dimension B can then be expressed as :

$$\sigma_B = \left[\sigma_L^2 + V_f^2 \sigma_{t_m}^2 + t_m^2 \sigma_{V_f}^2 + S_f^2 \left(\frac{\sigma_\chi^2}{\chi^2} + \frac{\sigma_{K_v}^2}{K_v^2} + \frac{\sigma_U^2}{U^2} + \frac{\sigma_{V_f}^2}{V_f^2} \right) \right]^{\frac{1}{2}} \quad (24)$$

(3) For given L

From Fig.2 the geometric relation for dimension B can be written as :

$$B = F - S_f \tag{25}$$

By using the tolerance transfer law, the standard deviation of B can be expressed as :

$$\sigma_B = \left[\sigma_F^2 + S_f^2\left(\frac{\sigma_\chi^2}{\chi^2} + \frac{\sigma_{K_v}^2}{K_v^2} + \frac{\sigma_U^2}{U^2} + \frac{\sigma_{V_f}^2}{V_f^2}\right)\right]^{\frac{1}{2}} \tag{26}$$

3. Computer Simulation of the Dimensional Accuracy

In order to analyze the dimensional accuracy of the workpiece in the ECM process the computer simulation has been performed by using the present theoretical models. The parameters used in the simulation of the dimensional accuracy are collected from the present experimental results and listed in Tables 1 and 2. The simulation results are shown in Figs (3-8) to present how the parameters affect the dimensional accuracy of the workpiece for each particular case.

Table 1 The parameters used in the simulation for standard deviation with no feed rate

No.	Parameter	Symbol	Value	Unit
1	Electrolyte conductivity	χ	0.0117	$A/v \cdot mm$
2	Volumetric electrochemical equivalent	K_v	1.91	$mm^3/A \cdot min$
3	Standard deviation of A	σ_A	0.01366	mm
4	Standard deviation of initial gap size	σ_{S_0}	0.01366	mm
5	Standard deviation of χ	σ_χ	0	$A/v \cdot mm$
6	Standard deviation of K_v	σ_{K_v}	0.0276	$mm^3/A \cdot min$
7	Standard deviation of U	σ_U	0	volt
8	Standard deviation of time	σ_{t_m}	0	min
9	Standard deviation of L	σ_L	0.0193	mm

Fig. 3 presents the simulation of the dimensional accuracy for the stationary ECM by using Eq. (7), which shows the effect of machining time on σ_B at different voltages. Fig. 4 is another simulation result using Eq. (10), which shows the effect of initial gap size on σ_B at different K_v. This trend has been attributed to the increase of MRR as a function of the increase in the time. The applied voltage has been found to have a direct proportional relationship with the

Table 2 The parameters used in the simulation for standard deviation of B with feed rate

No.	Parameter	Symbol	Value	Unit
1	Electrolyte conductivity	χ	0.0117	A/v.mm
2	Volumetric electrochemical equivalent	K_v	1.9	$mm^3/A.min$
3	Standard deviation of A	σ_A	0.01	mm
4	Standard deviation of S_0	σ_{S_0}	0.01	mm
5	Standard deviation of χ	σ_χ	0	A/v.mm
6	Standard deviation of U	σ_U	0.001	volt
7	Standard deviation of t_m	σ_{t_m}	0.00001	min
8	Standard deviation of V_f	v_f	0.001	mm/min
9	Standard deviation of K_v	σ_{K_v}	0.01	$mm^3/A.min$
10	Standard deviation of L	L	0.014	mm
11	Standard deviation of F	F	0.01	mm

$$\sigma_B^2 = \frac{1}{n-1}\sum_{i=1}^{n}(B_i - \bar{B})^2$$

where σ_B^2 is variance of B. B_i is the dimension of workpiece. $\bar{B}$ is sample mean. n is the sample size.

This expectation has been attributed to the increase of MRR at the high value of the applied voltages. Aninversely relation has been found between gap size and σ_B The increase of initial gap size leads to decrease of current and current density and causes MRR become less.

For transient state case (Figs. 5 and 6) it has been found that as feed rate, applied voltage and machining time increase, σ_B decreases. This result is due to the acceleration of the steady state condition. For steady state condition (Figs.7 and 8) it has been found that as feed rate increases and applied voltage decreases, σ_B decreases. This result is due to the decrease of the equilibrium gap value which usually leads to the increase of current density. Controllability of the process affects the value of the dimensional accuracy. The increase of electrolyte conductivity has led to the increase of σ_B because of the decrease of electrical electrolyte resistance which leads to higher metal removal rates.

4. Experimental Verification

The experiments were performed on an ECM cell, which consists of an electrolyte holding tank, a pump, power supply and appropriate hosing and pressure fittings to transport the electrolyte to and from the electrochemical cell. Measurements have been used to conduct the electrochemical accuracy experiments included an IBM compatible 386/25 MHz PC, conductivity and temperature probe meters (Orion, model 160), a precision laboratory scale

(Sartorius, E-1200S) with a readability of 0.1mg, and a state-of-the-art high speed data acquisition package (ISO-16) to collect data from the ECM cell. Brown & Sharp Microval Coordinate Measuring Machine (CMM) was used to measure the dimensions of workpiece after and before the ECM process.

The constructed ECM machining cell, consists of a cathode (tool) and the anode (workpiece) kept at a constant gap from each other by controlling the height of the tool with an accuracy of 0.01mm through CMM equipment. The cell was designed to withstanding a high electrolyte pressure. The constructed cell was made from stainless steel 304 and Teflon to avoid corrosion and to reduce the wear. Tool and workpiece holders were made from stainless steel (304 stainless steel). The specimen to be machined has a rectangular shape (workpiece height A=22.86mm, width b=3.073mm, length G=40mm and surface area of 122.8 mm^2). The specimens were made of ground die steel (Badger 01) produced in U.S.A.(0.94% Carbon, 0.3% Silicon, 1.2% Manganese, 0.5%

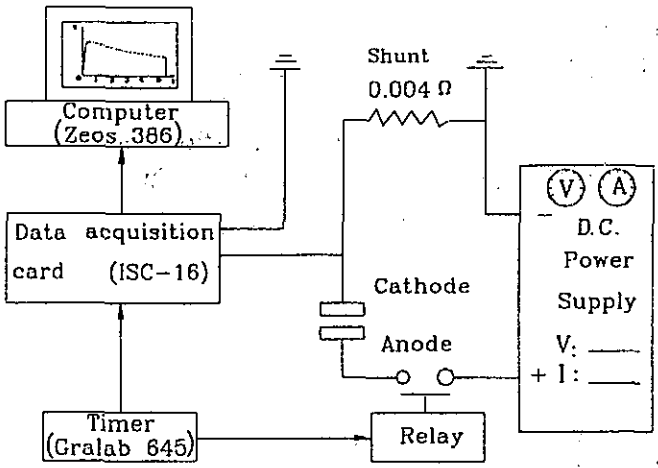


Figure 9 . Schematic diagram of the data acquisition system

Tungsten, 0.5% Chromium). The electrolytes used in these experiments were 15% $NaNO_3$ and 15% NaCl aqueous solutions (by weight) maintained at an initial temperature of 20°C. To overcome the problem of temperature rise during the ECM process a large quantity of electrolyte was pumped through the working gap to minimize the temperaturerise. The experiments have been done under the stationary tool feed rate.

The experimental set-up includes a precision engineered transistorized power supply. The generator is capable of supplying maximum current of 200 amperes, a voltage ranging from 5 to 30 volts with 0.5% RMS. ripple. This is controlled by a Siemens power relay which in turn is controlled by a Gralab 645 Digital timer for accurate machining time and easy control. An accurate machining timer was needed for calculating the material removal rates precisely.

Using the experimental set-up described above, the experiments on standard deviation of dimension of B were performed where the sample size for each value of standard deviation is 12. The standard deviation of B varying with the voltages, initial gap sizes, machining times and electrolyte have been obtained. These values are shown in Figs 10-13.

The present investigations have been carried out to optimize the dimensional accuracy in the ECM process specially under the stationary machining. Experimental test (Fig.10-13) revealed that the present analysis and simulation is adequate to predict the σ_B of the ECM process under different working conditions of applied voltage (Fig. 10), gap size (Fig. 11), machining time (Fig.12) and electrolyte type (Fig.13). The verification of σ_B was ranged from 0 μm to 5 μm for $NaNO_3$ and about 8 μm for NaCl.

5. Conclusions

- Dimensional accuracy in the ECM process has a complex nature due to the interaction of many parameters in the same time.
- Theoretical model and computer simulation proved its adequacy to improve the concept of dimensional accuracy through the computation of the standard deviation for all the working parameters.
- The present results provide the tool designer with the standard deviation of the basic parameters to control the dimensional accuracy of the ECM process.
- The present adopted technique could be extended to tolerance control in the ECM process and to control the removal of recast layer for EDM products surface by ECM action under controllable dimensional accuracy.

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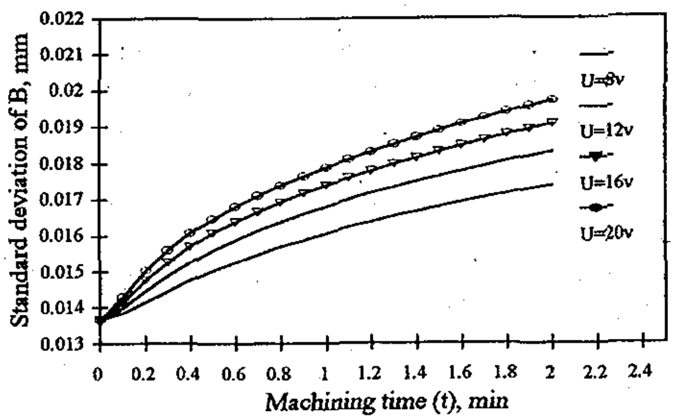

Figure 3 . Effect of the machining time on σ_B at different voltages

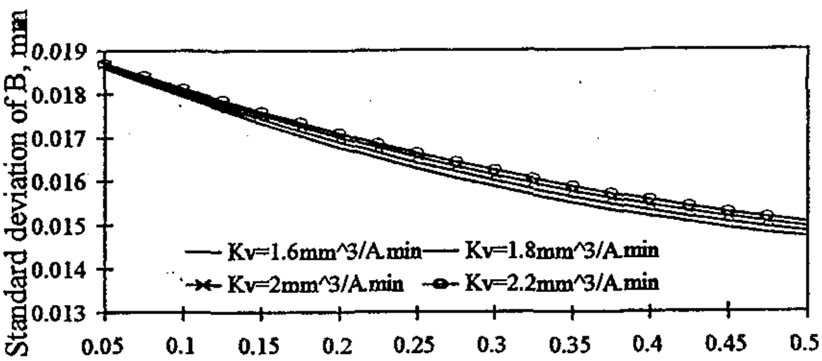

Figure 4 . Effect of initial gap size on σ_B at different K_v's

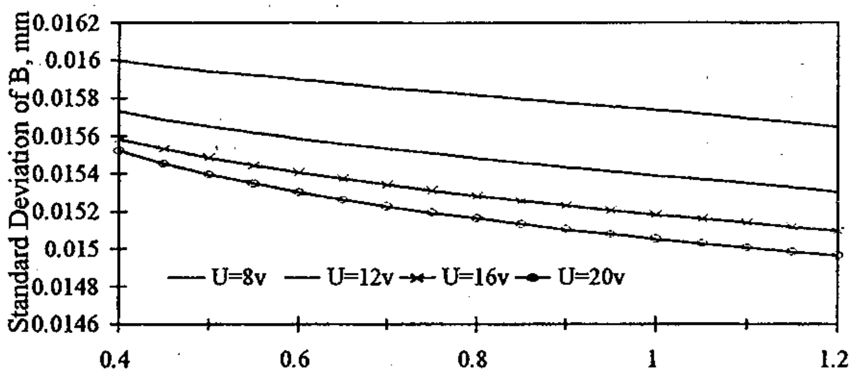

Figure 5 . Effect of feed rate on σ_B at different voltages

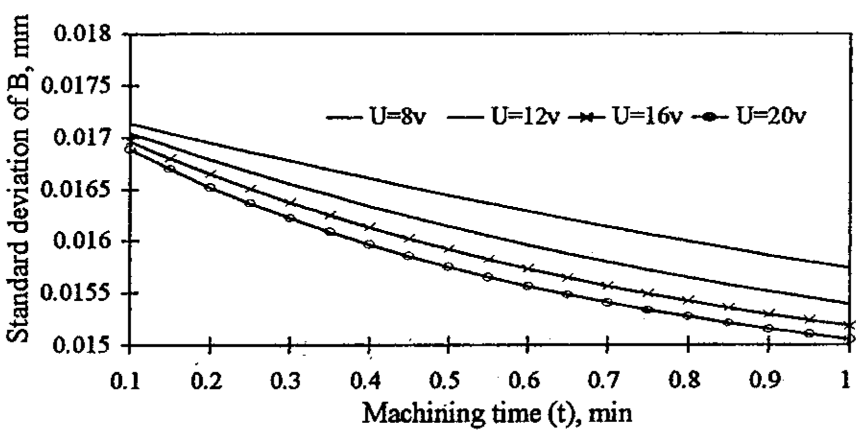

Figure 6 . Effect of machining time on σ_B at different voltages

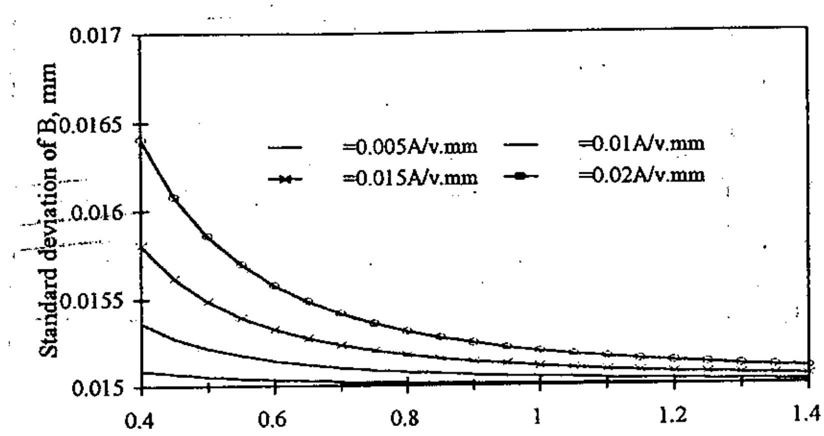

Figure 7 . Effect of feed rate on σ_B at different χ 's

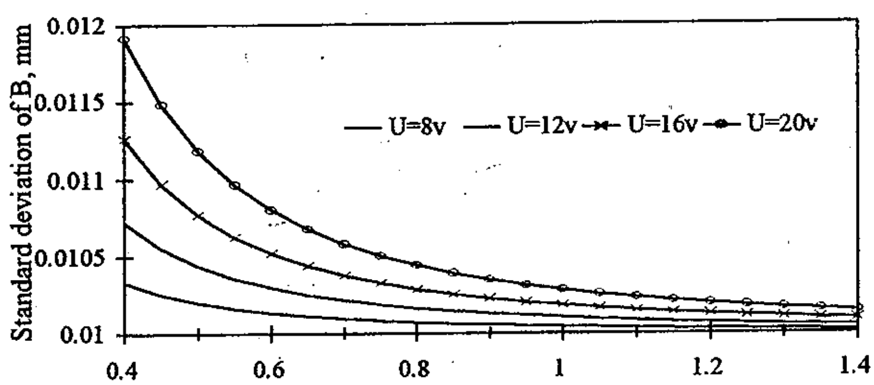

Figure 8 . Effect of feed rate on σ_B at different voltages

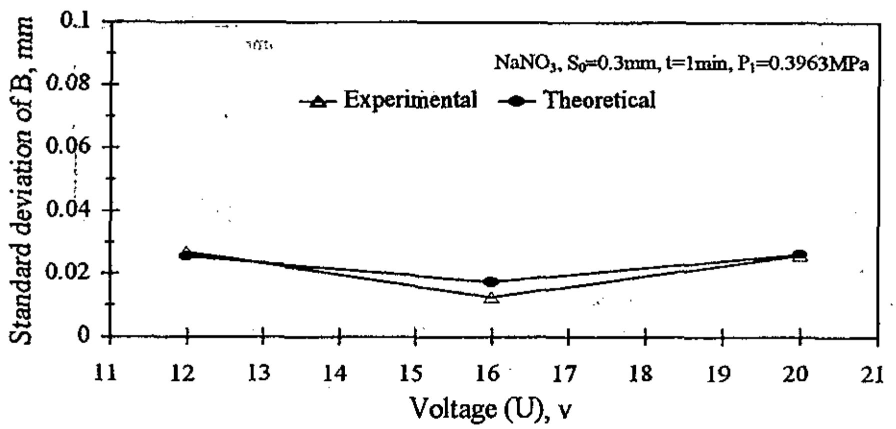

Figure 10 . Effect of applied voltage on σ_B

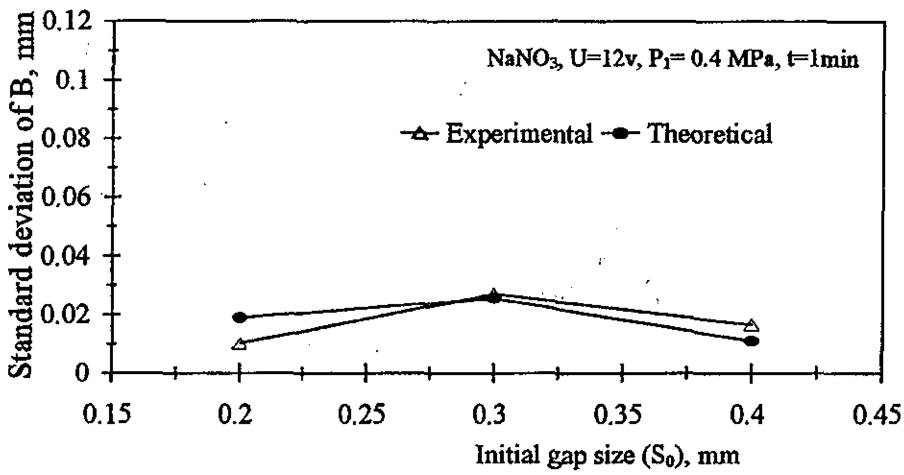

Figure 11 . Effect of initial gap size on σ_B

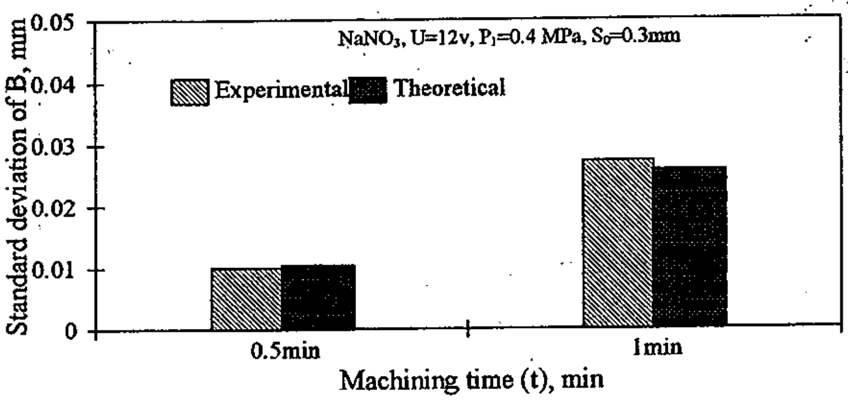

Figure 12 . Effect of machining time on σ_B

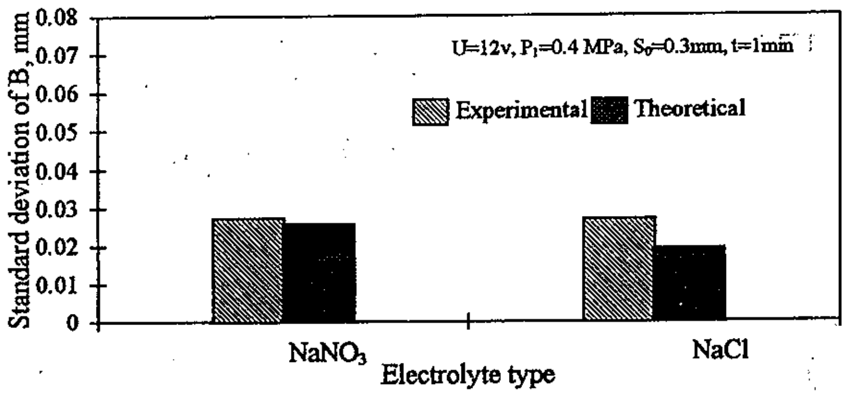

Figure 13 . Effect of the electrolyte type on σ_B

النمذجة و المحاكاة لدقة الأبعاد فى عمليات التشغيل الكهروكيميائى

* ك ٠ ب٠ روجاركار – ** م ٠ هويدى – و٠ ب٠ وى

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الملخـــــص

تعتبر دقة أبعاد المشغولات من أهم العوامل التى تعوق انتشـار التشـغيل الكهروكيميـائى بين الطرق الأخرى الغير تقليدية بالرغم من استخدامه فـى كثير مـن الصناعـات مثـل السيارات و صناعات الفضاء٠ و دقـة الأبعـاد هـى الفـارق بيـن أبعـاد الشـغلة الحقيقيـة والأبعاد المنتجة و ترتفع هذه الدقة كلما اقترب هذا الفارق مـن الصفـر ٠ و هـذا البحـث دراسة عملية و نظرية احتوت على كثير من عوامل التشغيل المختلفة مثل طول المنتج توصيلية المحلول الإليكتروليتى – درجة حرارة المحلـول – ضغـط المحلـول بالإضافـة الى نسبة غاز الهيدروجين و تأثيرها على التوصيلية٠

و قد أظهرت النتائج التى أجريت على أكثر من ٢٠٠ تجربة معملية أن دقة الأبعاد فـى التشغيل الكهروكيميائى ذات طبيعة معقدة لتداخل كثير من المتغيرات فى آن واحد و أن هذه النتائج تمد مصممى عدد التشغيل بالانحراف المعيارى للمتغيرات الأساسية ليتمكـن من التحكم فى دقة الأبعاد فى التشغيل الكهروكيميائى٠ كما أثبتت هذه الدراسة النظريـة مقدرتها على تحسين مفهوم دقة الأبعاد خلال حسـابات الإنحـراف المعيـارى لمتغيرات التشغيل٠