IMPROVING THE ACCURACY OF ELECTROCHEMICAL FORMING OF DIES AND MOLDS

H. El-Hofy and M.A. Younes

Production Engineering Department, Faculty of Engineering
Alexandria University, Alexandria - 21544 Egypt

ABSTRACT

Electrochemical machining (ECM) provides one of the best alternatives for producing complex shapes in advanced materials used in die and mold industries. This paper presents experimental assessment for the accuracy of shapes produced in high speed stationary electrochemical forming of holes into square shapes. Using a specially designed tool, a test cell is prepared for experimental verification, where the effects of machining voltage, removal allowance, tool geometry, removal rate and forming time are investigated. Dimensions, straightness of sides and corner radii of produced workpieces are evaluated and compared with corresponding theoretical values. The degree of shape conformity that reflects the level of process accuracy is also determined.

Keywords: ECM, Conformity factor, Tool profile, Workpiece profile, Straightness of sides.

INTRODUCTION

In electrochemical machining (ECM) difficult-to-cut materials and complex shapes are produced without distortion, scratches, burrs or stresses. ECM provides an effective alternative for producing a wide range of components such as aircraft turbine parts, surgical implants, bearing cages, molds and dies and even micro-components [1]. The shape of the tool electrode can be transferred onto, or duplicated-in the workpiece using EC-die sinking. Forging dies combining horizontal and slopping planes, cylindrical, spherical and complex shaped surfaces are typical applications of EC-die sinking with tolerances in the range of 0.1-0.3 mm.

The main objective in ECM research is to maintain the form errors as small as possible. This calls for the design of suitable tools, that will generate the required form and dimensions of finished parts under specific machining conditions. The most general method for calculating the shape produced, by a tool, involves the solution of Laplace equation for the field using iterative numerical methods, complex numbers [2] and finite element methods [3].

The large expenditure of electrical energy for dissolving the entire machining allowance and the use of considerable amount of electrolyte to remove the anodic products along the inter electrode gap limits the level of accuracy obtained. Actually, some metal is dissolved from the adjacent areas of the workpiece by the stray machining action thus causing form errors [4]. Such problems are reduced by using a tubular-section cathodic tools [5] or NC wire machines that utilize either ECM, EDM or EEDM [6,7]. Loskutove [8] improved the accuracy of holes by adding sodium tungestinate to sodium nitrate thus reducing both the end and lateral gaps. ECM accuracy can also be improved by replacing the dc by a pulsating voltage provided that the applied pulses are short enough and their duration is optimized to suit the gap size and electrolyte pressure [9].

Sizing of electrochemically drilled holes have been experimented using a moving tool during the combined electrochemical sinking-broaching process [10-11]. In a further work [12], tools for correcting hole shapes have been introduced. Changes in electrolyte conductivity due to the heating effects, development of gas bubbles in the electrolyte and the variation of the current efficiency with current density when using passivating electrolytes were not considered.

Reference [13] presented a tool profile for stationary machining of electrochemically drilled holes in order to produce definite geometry in the combined sinking sizing process. For stationary machining, the tool form depends on the distribution of the initial inter electrode gap if the shape and form of the finished part are specified in advance. The required tools are usually complicated, however they can be machined by NC wire EDM machines. In this work, the tool profiles presented in reference [13] are used to produce square holes from initially drilled cylindrical holes. The accuracy of shapes produced under variable gap voltage, removal allowance, tool geometry as well as machining time are evaluated. Accuracy measures in terms of shape conformity factors are also evaluated. The results obtained can be useful for the design of tools used in machining dies of complicated shapes.

EXPERIMENTAL CONDITIONS

Experiments were conducted using the set up shown in Figure 1. Hardened steel specimens 5 mm in height with initial hole of 13 mm diameter, and brass tools of calculated shapes are used, as seen in Figure 2. The experimental program is devised to investigate the effects of the forming voltage (V_f), the allowance removed (xl), the machining time (tm) and the tool geometry on the accuracy of machined parts. NaCl (170 g/liter) electrolyte is pumped under pressure to minimize the possible variation in its properties along the inter electrode gap.

During machining the weighed specimens were first located to be concentric with the specified tool and clamped in position. The electrolyte is pumped through the pressure chamber and the power is switched on. Machining current was monitored using an ammeter (100 A range), and the weight loss and machining time were used to determine the volumetric removal rate.

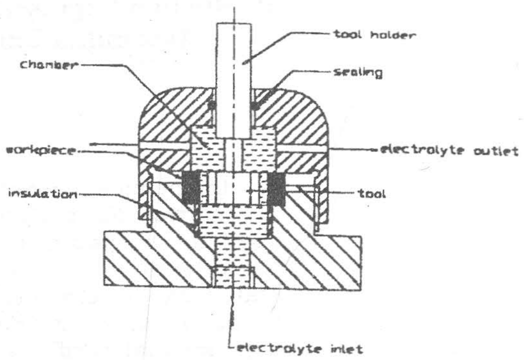


Figure 1 The machining cell

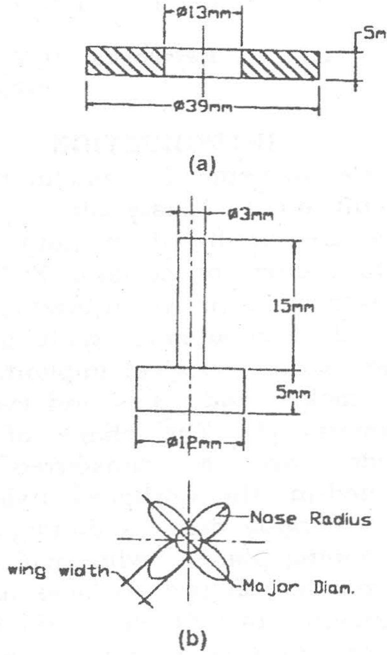


Figure 2 Shape and dimensions of, the workpiece (a), and tool (b)

In order to evaluate the accuracy of machined parts, the profile coordinates of both tools and workpieces, were determined before and after machining, using a digital profile projector that measures the dimensions down to 1μm. The relatively small dimensions of both tools and workpieces limited the use of CMM machines for the tool and workpiece measurement. The recorded coordinates were used to evaluate tool geometry including nose radius and wing width. Meanwhile, workpiece corner radii, out-of-straightens of sides, and diagonal deviations were also estimated using appropriate algorithms. Shape conformity factors are also calculated in terms of; a radial factor (r_1/r_2), an angular factor (θ_1/θ_2), and a linear factor (x_1/x_2), (see Figure 3).

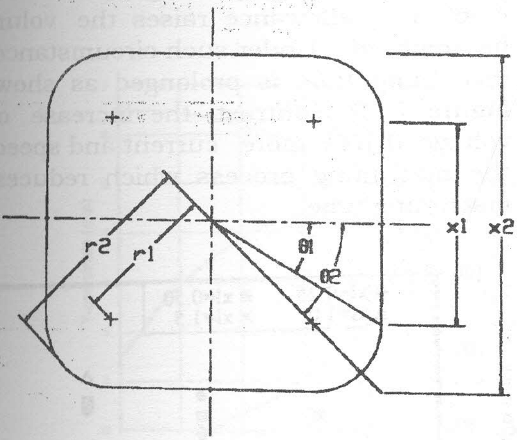


Figure 3 Main dimensions of machined hole

THEORETICAL MODELS AND ALGORITHMS

The profile of the tools necessary for producing the square shape from an initially drilled cylindrical holes are presented in Reference 13.

To calculate tool nose radius and the radius of curvature of workpiece corners a least squares approach was adopted [14,15]. If x_i, y_i are the profile coordinates at equiangular spacing from an assumed center, the sum of the squares of the deviations ($E_s = \sum E_i^2$) is given by, [14]:

$$E_s = \sum\{[(x_i - a)^2 + (y_i - b)^2]^{\frac{1}{2}} - R\}^2 \qquad (1)$$

$$E_s \approx (r_i - R - a\cos(\theta_i) - b\cos(\theta_i))^2 \qquad (2)$$

Where:

R: radius of curvature. a, b: estimated coordinates of the center of curvature.

$$r_i = (x_i^2 + y_i^2)^{\frac{1}{2}} \qquad (3)$$

$$\theta_i = \tan^{-1}\frac{y_i}{x_i} \qquad (4)$$

Solving for a, b and R, which will give the minimum value for E_s results in [14,15],

$$a = \frac{2\sum x_i}{n} \qquad (5\text{-a})$$

$$b = \frac{2\sum y_i}{n} \qquad (5\text{-b})$$

$$R = \frac{\sum r}{n} \qquad (5\text{-c})$$

Where:

$\sum x_i$: sum of all x_i values

$\sum y_i$: sum of all y_i values

n : number of measurement points

$\sum r_i$:sum of radial distances of measurement points from the least squares center (a, b).

On the other hand if x_i, y_i are the recorded coordinates for the workpiece sides, then the sum of the squares of the deviation of the side from a straight line is [16, 17],

$$L_s = \sum L_i^2 = \sum(y_i - \beta_o - \beta_1 x_i)^2 \qquad (6)$$

where:

β_o : intercept of the least squares line with the y-axis.

β_1 : slope of the least squares line.

Solving for β_o and β_1, which will give the minimum value for L_s [16]. Hence,

$$\beta_o = \bar{y} - \beta_1\bar{x} \qquad (7)$$

$$\beta_1 = [\sum x_i y_i - \frac{(\sum y_i)(\sum x_i)}{n}]/[\sum x_i^2 - \frac{(\sum x_i)^2}{n}] \qquad (8)$$

Where:

$$\bar{y} = \frac{1}{n}\sum y_i \qquad (9\text{-a})$$

$$\bar{x} = \frac{1}{n}\sum x_i \qquad (9\text{-b})$$

and the least square fitted line is $y = \beta_o + \beta_1 x$

The perpendicular signed deviation of each point from the fitted line is then calculated. Accordingly, the difference between maximum deviation and minimum deviation represents the out-of-straightness in the workpiece side.

RESULTS AND DISCUSSION

Metal Removal Rate

Figure 4 shows the effect of the gap voltage on the volumetric removal rate at different machining allowances. Accordingly, both theoretical and experimenntal volumetric removal rates increase with gap voltage. This trend is attributed mainly to the increase of the electrolyzing current as the gap voltage rises, (see Figure 5).

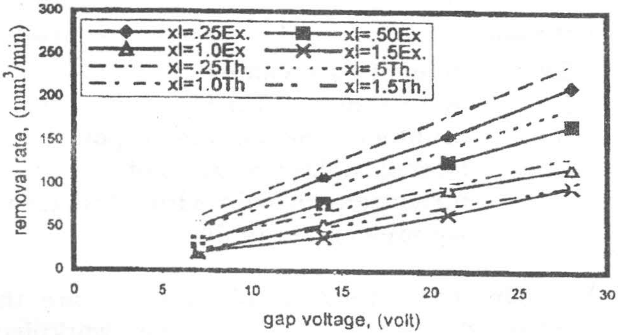


Figure 4 Effect of gap voltage on the volumetric removal rate at different machining allowance.

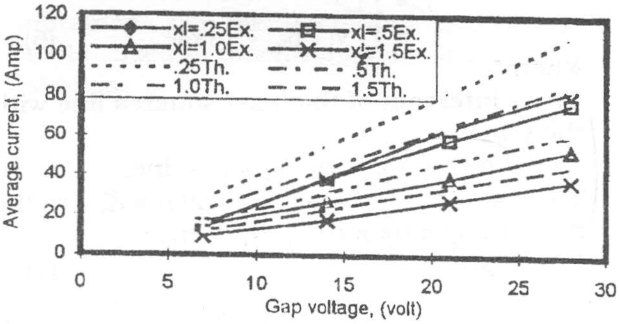


Figure 5 Effect of voltage on average current at diffeecnt machining allowance.

The theoretical values of machining current and hence the corresponding removal rates are greater than the experimental ones. This can be attributed to the assumptions made in the theoretical model, where effects of gas bubbles and heating are neglected [13]. Such differences are reflected on the current efficiency, shown in Figure 6, which rises with gap voltage and reaches 90% aproximately at 28 gap voltage. This rise can be attributed to Joule's heating that raises the electrolyte conductivity and hence more current is used in the metal removal process. The same figure shows no clear trend to the current efficiency at different machining allowance.

Regarding the effect of machining allowance on both the removal rate and machining current, it can be seen that, as the machining process continues, the allowance increases, the interelectrode gap becomes wider and consequently the average machining current and hence the removal rate decrease.

For a given gap voltage, the increase of machining allowance raises the volume to be removed. Under such circumstance, the machining time is prolonged as shown in Figure 7. In contrast, the increase of gap voltage drives more current and speeds up the machining process which reduces the machining time.

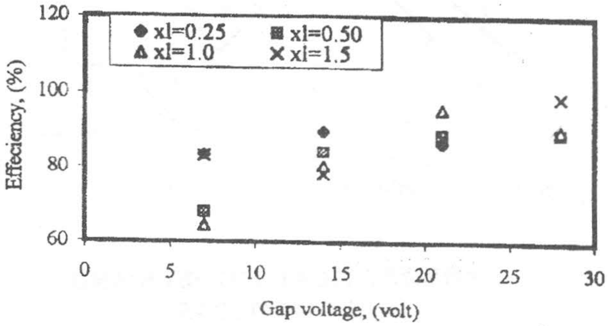


Figure 6 Effect of gap voltage on the current effeciency at different machining allowances

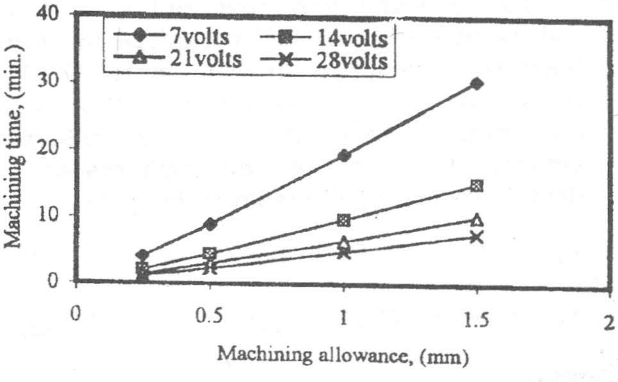


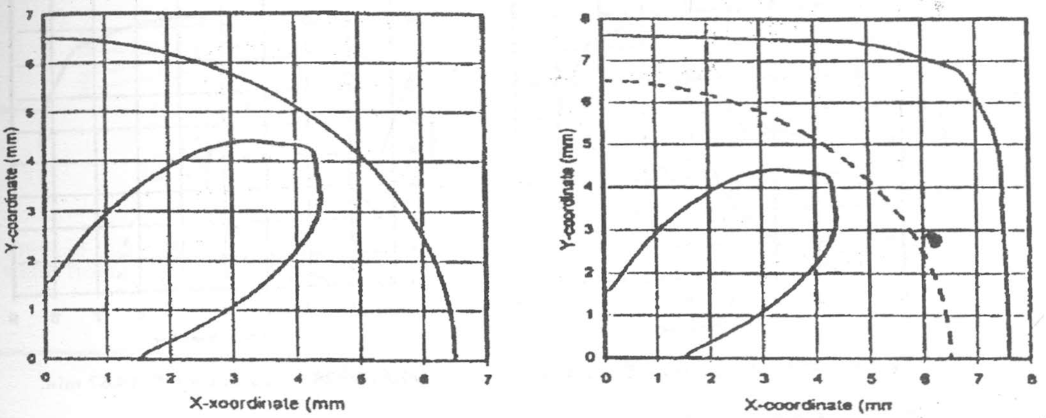
Figure 7 Effect of machining allowance on machining time at different gap voltages

Process Accuracy

a- Effect of process parameters

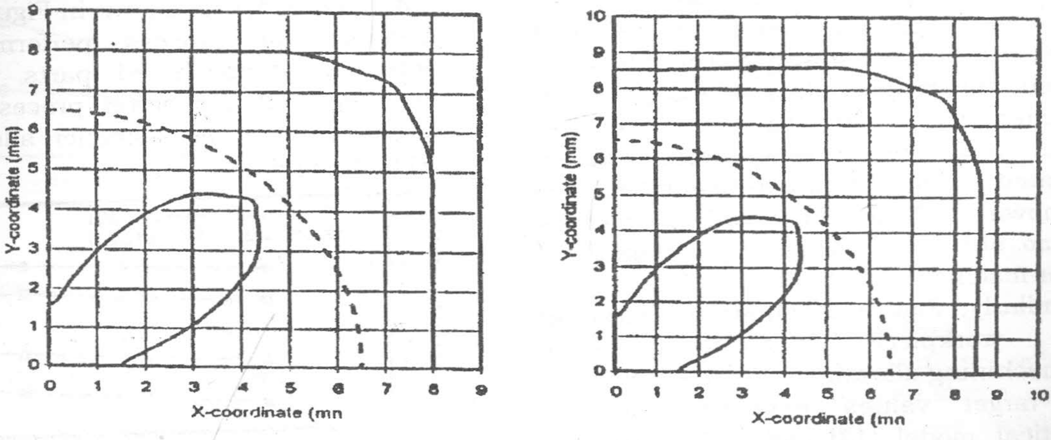
Figure 8 shows the variation in the workpiece profile with machining time, for the gap voltage of 21 volts. The profile which is originally a circle, Figure 8-a changes with progress of time and becomes of square sides after 10.67 min. as described by the theoretical model, (Figure 8-c). Further increase of machining time detriorates the geometry of the shape produced as shown in Figure 8-d.

Figure 9 illustrates also the variation in workpiece profile with gap voltage at a machining time of 10.67 min. It can be concluded that for certian gap voltage there exists an optimum machining time (10.67 min. for 21 volts) which is confirmed from the shape obtained in Figure 9-c. A reduction in gap voltage would, correspondly, raise the time and visa versa. The final workpiece profile contains rounded corners, the radius of which depends on both the gap voltage and machining allowance.



(a) At V= 21 volt, and time T= 0 min.

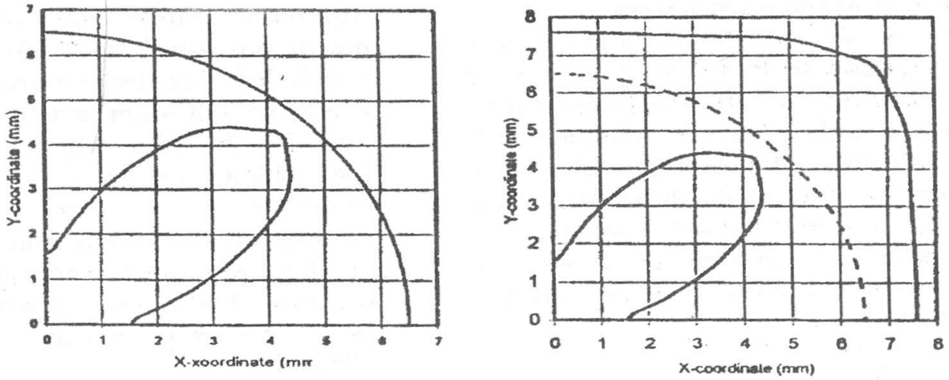
(b) At V= 21 volt, and time T= 5 min.



(c) At V= 21 volt, and time T= 10.67 min.

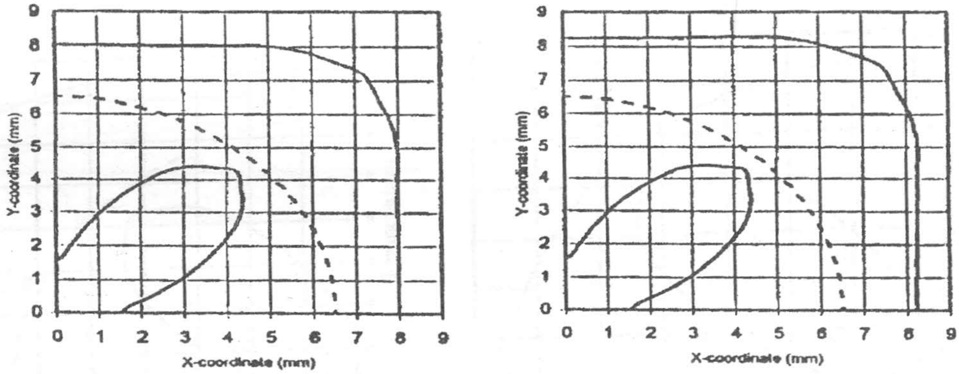
(d) At V= 21 volt, and time T= 15 min.

Figure 8 Effect of machining time on workpiece profile, (v=21 volts)



(a) At V= 0 volt, and time T= 10.67 min.

(b) At V= 7 volt, and time T= 10.67 min.



(c) At V=21 volt, and time T= 10.67 min.

(d) At V=28 volt, and time T=10.67 min.

Figure 9 Effect of gap voltage on workpiece profile, (T=10.67 min)

Figure 10 depicts the increase of corner radius at high machining voltage and smaller machining allowance. The difference between the corner radius values evaluated experimentally using the least squares model and the corresponding values calculated using the theoretical model [13] are shown in Figure 11. Smaller deviations are also observed at larger gap voltages and smaller machining allowance.

Similarly, Figure 12 shows the variation of the workpiece width with gap voltage and machining allowance. Smaller deviation from target values described by the theoretical model [13] can be obtained at machining voltages greater than 21 volts probably due to the high current efficiency observed under such conditions as shown in Figure 6.

The effect of gap voltage and machining allowance on the straightness error of the produced sides is shown in Figure 13. As a measure of process performance and accuracy of machined parts, it can be depicted that, for better process outcome larger voltage and smaller allowance are recommended.

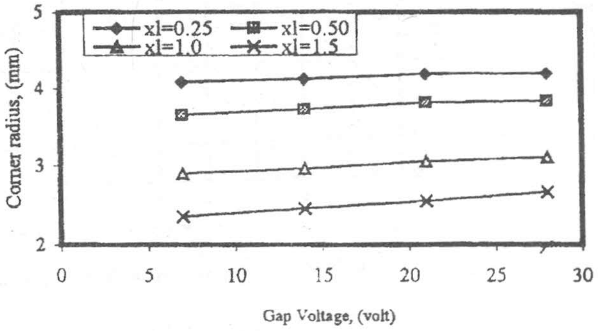


Figure 10 Effect of gap voltage on corner radius atesretical different machining allowances

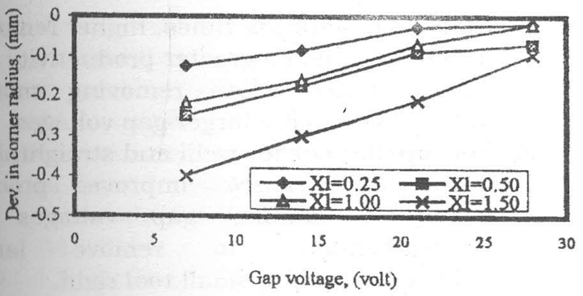


Figure 11 Deviation in corner radius from theoretical values at different gap voltages

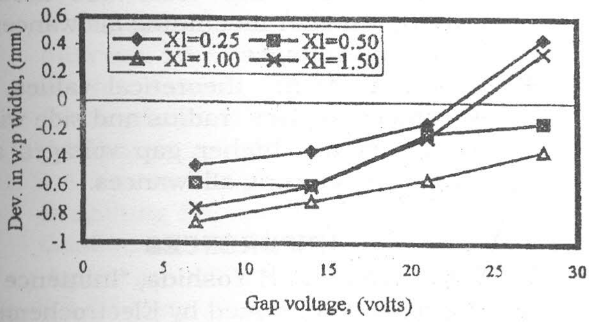


Figure 12 Effect of Gap voltage on the deviation in w.p width from theoretical values

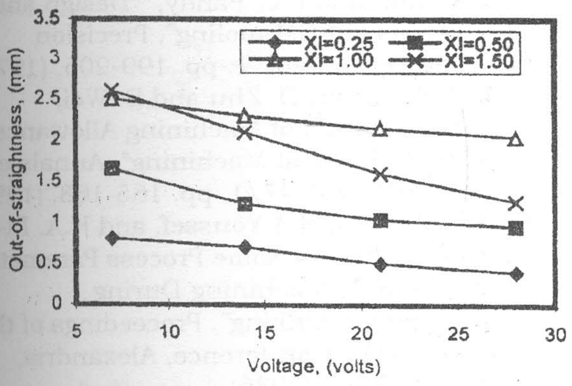


Figure 13 Out of straightness at different voltages and gap allowances

b- Effect of sizing tool geometry:

The geometry of sizing tools, in terms of nose radius and wing width, (see Figure 2), affects the produced workpiece geometry. The effect on both workpiece corner radius and straightness error of resulting sides are evaluated for different gap voltages. The effect of tool nose radius on workpiece corner radii is shown in Figure 14. Accordingly, larger tool nose radius and great gap voltage produce larger workpiece corner radii as greater cathodic tool arc length conducts more machining current to the anodic surface leading to a larger corner radius. Moreover, the deviation in straightness of workpiece sides from the corresponding theoretical values increases with tool wing width as shown in Figure 15. Therefore narrow tool wings of smaller nose radii are recommended for producing better shape conformity.

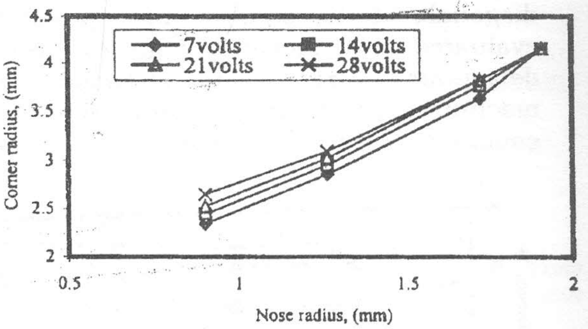


Figure 14 Effect of tool nose-radius on w.p. corner-adius at different gap voltage

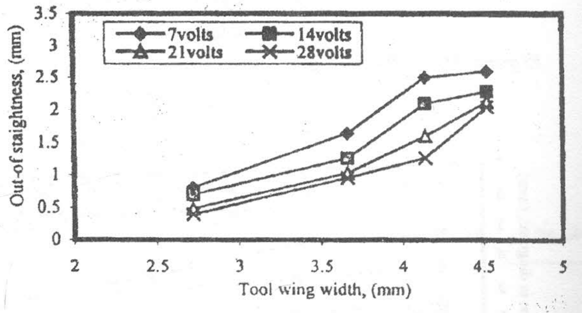


Figure 15 Effect of tool wing-width on w.p. out-of-straightness at different gap voltages

Shape Conforomity Factors

The conformity factors reflect the changes in the produced shape as a result of the formation of corner radius. Three factors are introduced, as seen in Figure 3. In terms of straight edge length, (linear factor), radial position of corner center, (radial factor), and the angle of the produced corner,(angular factor). Each of these factors can be calculated in terms of other ones, using simple trigonometric relationships.

Figure 16 shows the radial conformity factor at different gap voltages as well as machining allowances. The greater the factor, the smaller the corner radius produced and the better the produced articles. That ultimate goal can be achieved when removing larger machining allowances using higher machining voltages. However, the effect of gap voltage is very small, (less than 2%). Similar observations are also reported with respect to both the linear and angular conformity factors. Error in the diagonals of the square holes produced is evaluated and shown in Figure 17. Smaller deviations are also obtained when machining at larger gap voltages to remove small machining allowances.

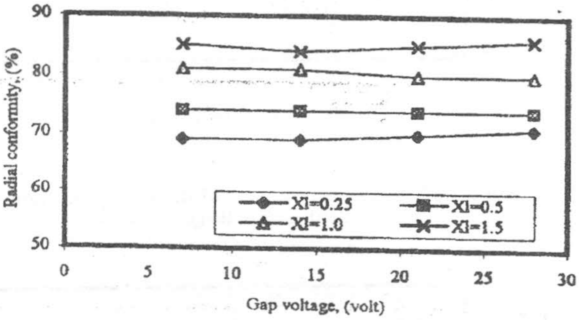


Figure 16 Effect of gap voltage on radial conformity factor at different machining allowances

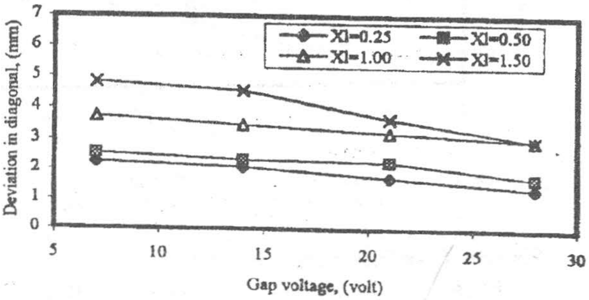


Figure 17 Effect of gap voltage on deviation in w.p. diagonal at differen machining allowances

CONCLUSIONS

From the results obtained under the conditions decribed in this work it can be concluded that:

1. Smaller machining times, higher removal rates and hence greater productivity can be obtained when removing smaller allowances using larger gap voltages.
2. For smaller corner radii and straightness error and hence improved process accuracy, smaller gap voltages are recommended to remove larger allowances using small tool radii.
3. Out-of-straightness of workpiece sides and deviation in its diagonals decrease when narrow-wing tools are used to remove smaller machining allowances at larger gap voltages.
4. Deviation, from theoretical values, in workpiece corner radius and side width decreases at higher gap voltages and smaller machining allowances.

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تحسين دقه الاسطمبات والقوالب المشكلة بعملية التشغيل الكهروكيميائي

حسن الحوفى و محمد يونس
قسم هندسة الانتاج - جامعة الاسكندرية

ملخص البحث :

يمثل التشغيل الكهروكيميائي أحد أفضل البدائل المستخدمة لإنتاج الأشكال المعقدة عند تصنيع الاسطمبات والقوالب من مواد مستحدثة. وتمثل هذه الدراسة تقييم عملي لدقة الأشكال المنتجة بالتشكيل الكهروكيميائي لتحويل الثقوب الأسطوانية إلى مربعة المقطع بإستخدام أدوات مصممة خصيصا لهذا الغرض . وقد تم تجهيز خلية تشغيل كهروكيميائي للتحقيق من كفاءة أداء الأدوات المستخدمة مع دراسة تأثير كل من : جهد التشغيل الكهروكيميائي ، سماح التشغيل ، الشكل الهندسى لأداة القطع، معدل إزالة الراش ، بالإضافة إلى زمن التشغيل على جودة الأجزاء المنتجة. وقد تم تنفيذ مجموعة من التجارب لدراسة تأثير العناصر المشار اليها، ثم قياس أبعاد وشكل الأجزاء المنتجة.

وتم تقييم أبعاد الثقب الناتج واستقامة جوانبه وتقوس الأركان ومقارنة القيم التى تم الحصول عليها عمليا بما يقابلها من القيم المحسوبة نظريا ، كما تم تقدير مدى مطابقة الشكل الناتج بالشكل المحسوب نظريا وبما يعكس مستوى دقة العملية المستخدمة .

ويتضح من نتائج الدراسة ومقارنة القيم التى تم الحصول عليها بما يقابلها من القيم المحسوبة نظريا النقاط الرئيسية التالية :

١ - يمكن تحقيق أزمنة تشغيل قصيرة ، ومعدلات إزالة عالية للمعدن وبالتالى إنتاجية عالية إذا كان سماح التشغيل صغير والجهد المستخدم عالي.

٢ - للحصول على تقوس صغير لأركان المنتج واستقامة عالية للحواف مع دقة أداء أفضل للعملية ، يوصى باستخدام جهد منخفض عند إزالة سماحات تشغيل كبيرة بإستخدام أدوات ذات تقوس صغيرة لمقدمة الأجنحة .

٣ - يقل الانحراف فى استقامة الحواف والأقطار المنتجه عند استخدام أدوات ذات أجنحة ضيقة لإزالة سماحات تشغيل صغيرة مع جهد كهربي عالي .

٤ - يقل الانحراف فى تقوس الأركان وطول ضلع المربع المنتج عن القيم النظرية المناظرة عند استخدام جهد كهربي عالى وسماح التشغيل صغير .

والدراسة تساعد فى تحديد ظروف تشغيل يمكن استخدامها للحصول على أشكال وتجاويف متعددة عند تصنيع الاسطمبات والقوالب بإستخدام عملية التشغيل الكهروكيميائي .