TOWARDS ELECTROCHEMICAL MACHINING OF DIES AND MOLDS

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ABSTRACT

This paper presents a tool design for high speed stationary electrochemical machining of holes into geometrical shapes. A test cell is prepared for the experimental verification. The effects of machining voltage, removal allowance on tool geometry, removal rate and, machining time are investigated.

Keywords: Machining allowance, Sizing time, Geometrical shapes, Interelectrode gap.

NOMENCLATURE

A	Atomic weight.
C	Material constant.
Cr	Workpiece corner radius, mm.
F	Faraday's constant, 96500 A.s/gm. equivalent.
go	Initial gap, mm.
Ip(t)	Machining current, A.
Ns	Number of sides.
rc(θ)	Tool radius at an angle θ, mm.
R	Initial hole radius, mm.
Rt(t)	Gap resistance at time t, Ω.
rs	Cathode tool holding radius, mm.
tp	Forming time, min.
tx	Maximum possible time, min.
V	Applied voltage, Volt.
Vw	Volumetric removal rate. mm^3/min.
X	Machining allowance, mm.
Z	Valency of workpiece material Fe^{2+}.
ϵ	Electrochemical equivalent, mm^3/C.
κ	Electrolyte conductivity, Ω^{-1} mm^{-1}.
ρ	Density of material gm/mm^3.
θs	Corner angle of shape produced.

INTRODUCTION

Electrochemical machining ECM is a method of removing metallic machining allowance by anodic dissolution. Metal removal is affected by a suitably shaped tool electrode, and the parts thus produced have the specified shape, dimensions and surface finish. EC-die sinking is carried out so that the shape of the tool electrode is transferred onto, or duplicated-in the workpiece. For high accuracy, in shape duplication and enhanced metal removal rate, the process must be achieved at high current densities, while maintaining narrow machining gaps, by feeding the tool electrode in the direction of metal removal from the anodic surface. Forging dies combining horizontal and sloping planes, cylindrical, spherical and complex shaped surfaces with easements varying in radii are typical applications of EC-die sinking. Die cavities having slopes ranging from 3°-12° for the outside walls and 5°-15° for the inner ones can be machined with tolerances of $\pm$ 0.1 to $\pm$ 0.3 mm.

In EC-die sinking the machining allowance is subjected to anodic dissolution that requires high power sources to supply a sufficient current density over the entire machined area of the workpiece. In addition, the large expenditure of electrical energy for dissolving the whole allowance and, the use of considerable amount of electrolyte to remove the anodic products along the inter electrode gap form major problems. Such difficulty has been encountered when producing large-size cavities by using a tubular-section cathodic tool [1-2] or NC wire machines that utilize either electrochemical machining, ECM, electrodischarge machining, EDM, or electroerosion dissolution machining, EEDM [3-5].

When EC-machining of complicated shapes, it is not easy to duplicate the shape of the tool in the workpiece. Hence, obtaining high degree of accuracy hinders wide application for the ECM process because there is a difficulty in confining the process precisely within the machined area. Some metal is dissolved from the adjacent areas of the workpiece by the stray machining action [6-7].In this regard, Loskutove [8] improved the accuracy of holes by adding sodium tungestinate to the sodium nitrate solution thus reducing both the end and lateral gaps.

In ECM, the main objective is to maintain the form tolerances as closely as practicable. This calls for the design of a suitable tool, and in consequence, the computation of the form and dimensions of the finished parts to be generated with that particular tool and working conditions. This design is mainly influenced by the formation of the gap between the tool and workpiece through which the electrolyte flows. ECM tooling design is basically concerned with tool profile computation, that, produces the desired workpiece shape and size. The accurate design of tool electrode is affected by the lack of knowledge about some quantitative aspects of the events occurring in the inter electrode gap and the mathematical difficulties in solving the field problems. In practice, the approximate shape of such a tool is therefore obtained by standard computational techniques to which certain corrections, based on practical considerations and shape complexity, are added. In this manner, the practice of designing ECM tools by trial and error is costly and time consuming. The mathematical methods describing the ECM process of metals, alloys and composites have been advanced for the design of tool electrodes and control of process parameters. Recent years have also seen the emergence of ECM manufacturing centers and computer aided design of tool electrodes .

The shape produced by the ECM tool is dependent on the non uniform current field between the two electrodes. Methods of calculating the filed strength and hence current distributions are well understood but unless the electrode shape is simple, these methods are not easy to apply. The most general method for calculating the shape produced, by the tool, involves the solution of Laplace's equation, for the field, using iterative numerical methods, complex numbers [9] and finite element methods [10]. Even with these techniques the electrodes are considered equipotential surfaces. The variation in the electrical conductivity of the machining medium, filling the machining gap, has been minimized and the process accuracy increased, when the dc voltage was replaced by a pulsating voltage provided that the applied pulses are short enough and the pulse duration is optimized to suit both the gap size and electrolyte pressure [11].

Mechanical machining of most strength members on a duplicating milling machine or NC machine tools entail a number of manual finishing operations that can be eliminated by employing ECM. A glassware has been electrochemically machined with an uninsulated tool electrode at a low gap voltage and passivating electrolyte. The mold blank was firstly bored leaving an appropriate allowance for the subsequent finishing process. The dimensions of the tool were reduced by an equal amount, proportional to the specified dimensions of the required shape [11]. In this mode of machining the allowance to be removed was small and, consequently, small power supplies were used. In order to ensure high productivity and accuracy a two-stage ECM method has been proposed [12]. Accordingly, dilute electrolytes were firstly used at high current density which was followed by a finishing stage at low current density.

Sizing of electrochemically drilled holes have been experimented using a moving tool during the combined sinking-broaching process [13]. In a further work [14[, tools for correcting hole shapes have been also 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. Such a model can, however, be justified when using a stationary tool in a stagnant electrolyte. The machining cycle was made of two phases where dissolution occurs in the stagnant electrolyte and the removal of dissolution products, by a stream of electrolyte, was achieved while the current is turned off. Flushing away the machining products minimizes the variations in electrolyte conductivity and raises the process accuracy [13,14].

This work presents a tool electrode for stationary machining of electrochemically drilled holes in order to turn them into definite geometrical shapes, in the combined sinking sizing process. Effects of machining voltage, time and allowance on the cathodic tool form when producing triangular, equilateral, square, pentagon and hexagonal shapes are introduced. Profiling current and volumetric removal rate together with the process accuracy are also presented.

For the 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. In this manner tools for machining dies of complicated shapes can be determined. The resulting tools, however complicated, can be conventionally machined, relatively easy compared with the female form that is to be made from difficult-to-machine materials. These tools can be produced using NC wire EDM machines and computer aided programming thus cutting down the working hours by 60 % while improving the machining accuracy [11].

THEORETICAL MODEL:

Figure (1) shows the EC-drilled hole of radius R. The workpiece is made concentric with tool of radii rc(θ). The gap of varying width, is filled with the electrolyte of conductivity κ. With the progress of machining, the workpiece radii ra(θ,t) change as described by Tipton [15]:

$$\frac{dra(\theta,t)}{dt}=\frac{C}{ra(\theta,t)\ln\left(\frac{ra(\theta,t)}{rc(\theta)}\right)} \tag{1}$$

where $C = \varepsilon\kappa V$

and $$\varepsilon=\frac{A}{ZF\rho}$$

A : Atomic weight.
F : Faraday's constant.
Z : Valency of workpiece.
ρ : Density of workpiece.

The tool profile needed for changing the circular hole into any shape described by ra(θ,t) in time t is given by:

$$rc(\theta)=\frac{ra(\theta,t)-R^2-2Ct}{2[ra(\theta,t)-R]} \tag{2}$$

The time required for such a change is described by;

$$t=\frac{ra^2(\theta,t)-R^2+2Rrc(\theta)-2rc(\theta)ra(\theta,t)}{2C} \tag{3}$$

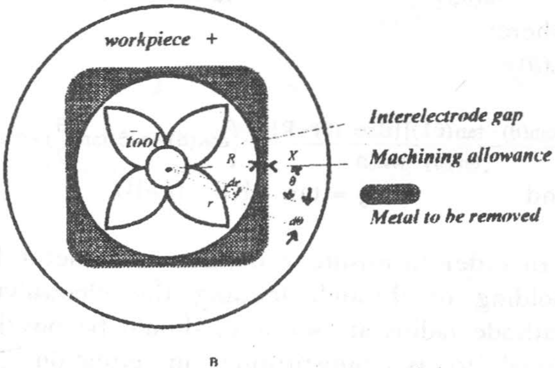
Referring to Figure (1), the time tp necessary to change the circular hole to any shape of Ns equal sides and, a corner radius Cr can be calculated by using equation (3), based on the assumption that:

$$rc(\theta s) = R - go$$

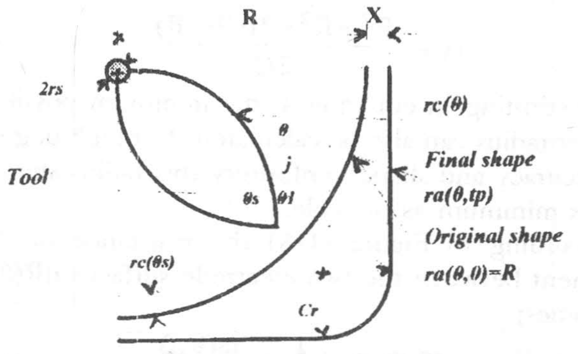
$$ra(\theta s,t) = B\sec(\theta s)-1$$

$$\lambda = Cr\,[\sec(\theta s)-1]$$

$$\theta s = 180/2Ns$$



(A) Machining square shape from circular hole



(B) Interelectrode gap configuration

Figure 1. Theoretical model for ec-machining.

The profiling time tp then becomes;

$$tp = \frac{[B\sec(\theta s) - \lambda]^2 - R^2 + 2R(R-go) - 2(R-go)[B\sec(\theta s) -}{2C} \qquad (4)$$

where B = R + X

Based on the time tp, Cr and the allowance X the cathodic tool radii at any position between $\theta = 0$ and θ can be calculated by;

$$rc(\theta) = \frac{(B\sec(\theta))^2 - R^2 - 2Ctp}{2(B\sec(\theta) - R)} \qquad 0 \leq \theta \leq \theta 1 \qquad (5)$$

$$rc(\theta) = \frac{[B\sec(\theta) - L(\theta)]^2 - R^2 + 2Ctp}{2(B\sec(\theta) - L(\theta) - R)} \qquad \theta 1 \leq \theta \leq \theta s \qquad (6)$$

The anodic workpiece profile can then be calculated by;

$$ra(\theta, tp) = B\sec(\theta) \ldots\ldots\ldots\ldots\ldots\ldots 0 \leq \theta \leq \theta 1$$

$$ra(\theta, tp) = B\sec(\theta) - L(\theta), \ldots\ldots\ldots\ldots\ldots \theta 1 \leq \theta \leq \theta s \qquad (7)$$

where;

$L(\theta)$=

$$\frac{[\tan(\theta) - \tan(\theta 1)][B\sec(\theta) - R]}{\tan(\theta) - \tan(j)}\left[1 - \left(\cos(\theta)\sin(\theta)\tan(\frac{\theta}{2}) + \cos^2(\theta)\right)\right] \qquad (8)$$

and $j = \tan^{-1}(R\sin(\theta)/B)$

In order to ensure a minimum diameter for tool holding or through feeding the electrolyte, the cathode radius at θ=0, rc(0) should be positive and equal to rs. Substituting in equation (4) the maximum machining time tx becomes

$$tx = \frac{B^2 - R^2 - 2rs(B - R)}{2C} \qquad (9)$$

Substituting in equation 4, the minimum possible corner radius can also be calculated. For high degree of accuracy and shape conformity this radius should be as minimum as possible.

According to Figure (1-A) the resistance of the element between the two electrode surfaces $dR(\theta,t)$ becomes;

$$dR(\theta, t) = \frac{1}{kd\theta}\ln\frac{ra(\theta, t)}{rc(\theta)} \qquad (10)$$

For a shape having Ns sides the total gap resistance is given by;

$$\frac{1}{Rt(t)} = 2kNs\int_0^{\theta s}\frac{d\theta}{\ln\left(\frac{ra(\theta, t)}{rc(\theta)}\right)} \qquad (11)$$

Applying an effective voltage V the machining current Ip(t) would pass causing the volumetric removal rate Vw

$$Vw = \epsilon\int_0^{tp} Ip(t)\,dt \qquad (12)$$

EXPERIMENTAL CONDITIONS:

Experiments were conducted using the set up shown in Figure (2). Hardened steel specimens of 6 mm height were used. Their chemical composition (%) contains 1.27 C, 0.15 Si, 0.27 Mn, 0.06 Cr, 0.02 Ni, 0.014 Ph, 0.05 Cu and 0.011 S. Brass tools of the specified shapes were calculated using the given model and a computer program. Figure (3) shows some of these forms together with their testing conditions. The experimental program was devised to investigate the effect of machining voltage, allowance removed, machining time on the workpiece geometry using NaCl of 170 g/l, flowing at 30 l/min. The electrolyte was pumped under pressure of 0.3 Mpa to minimize the possible variation in its properties along the inter electrode gap.

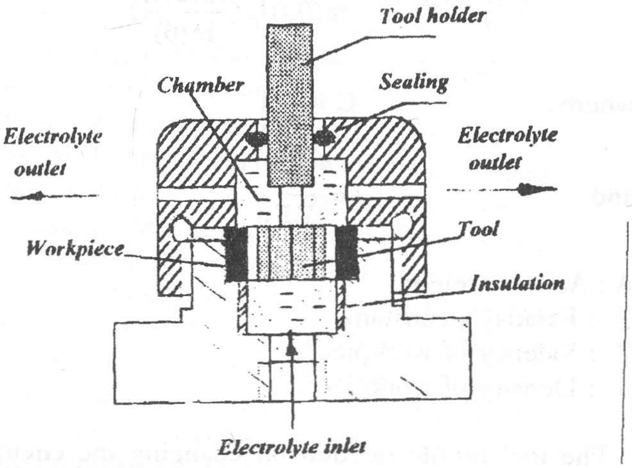
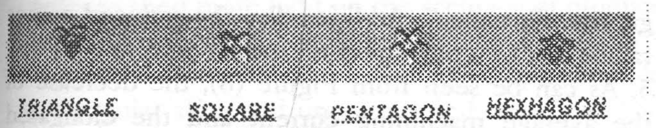


Figure 2. The experimental set-up.



WORKING COND.
ELECTROLYTE: NaCl
ALLOWANCE: 1 MM
INITIAL GAP: 0.5 MM

Figure 3. Tool forms used.

During machining the weighted specimens were first located concentric with the specified tool and clamped in position. The electrolyte was pumped through the machining chamber and the power was switched on. Machining current was monitored. The weight loss and the machining time were used to determine the volumetric removal rate. Workpiece profiles were also measured using a shadow projector.

RESULTS AND DISCUSSIONS

Figure (4) shows the effect of machining voltage on the time required to change the hole to square and hexagonal shapes. The machining allowance X , initial gap go and, the electrolyte conditions were kept constant. For both shapes, the use of higher voltage reduces the machining time. Under a given voltage the time needed for obtaining hexagonal shape, is smaller than that for the square one.

This trend can be explained using the results of Figure (5) since the raised voltage enhanced the removal action and produced higher removal rates. Generally the increase of removal rate with machining voltage can be explained using Faraday's laws and the machining current trend described in Figure (6). For both shapes the increase of voltage allows for more current to pass between the two electrodes. Moreover, for the hexagonal shapes, the increased current together with the reduced machining time, Figure (4), justify the enhanced removal rate due to the large number of active edges (Ns=6). The experimental current was higher than that calculated from the model probably due to the differences in electrolyte temperature and pressure. Such a deviation becomes smaller when machining hexagonal shapes. It should be mentioned here that due to the limited capacity of the power supply used (50 A) it was not possible to machine hexagonal shapes at higher voltage than that described in Figure (5). Regarding the experimental and theoretical metal removal rates, it can be postulated that the introduced model fairly describes the metal removal process.

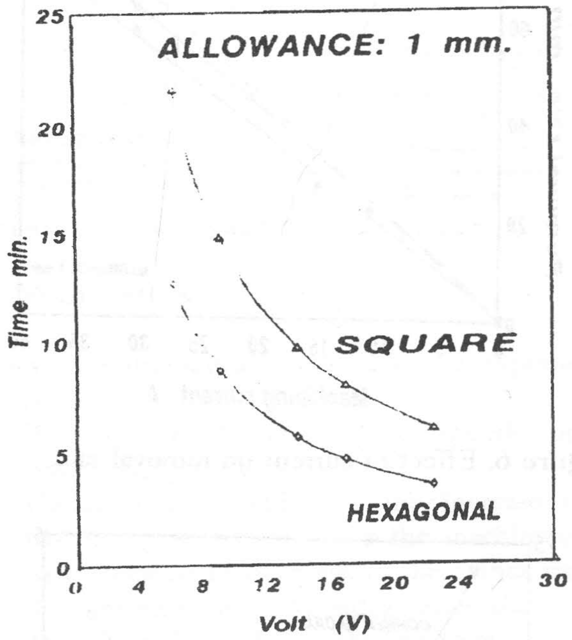


Figure 4. Effect of voltage on machina time.

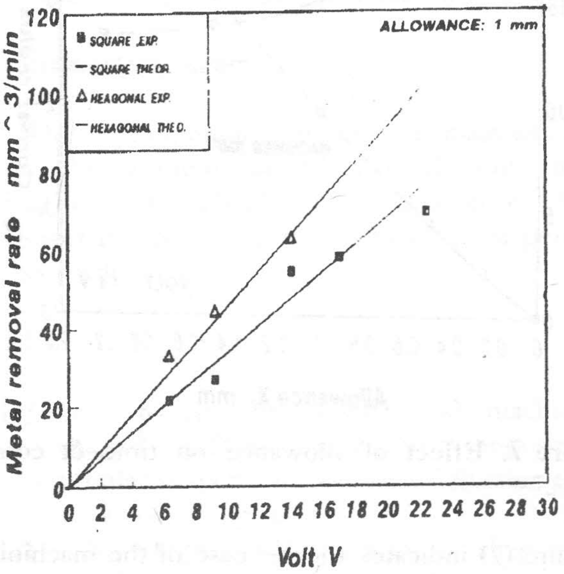


Figure 5. Effect of voltage on removal rate.

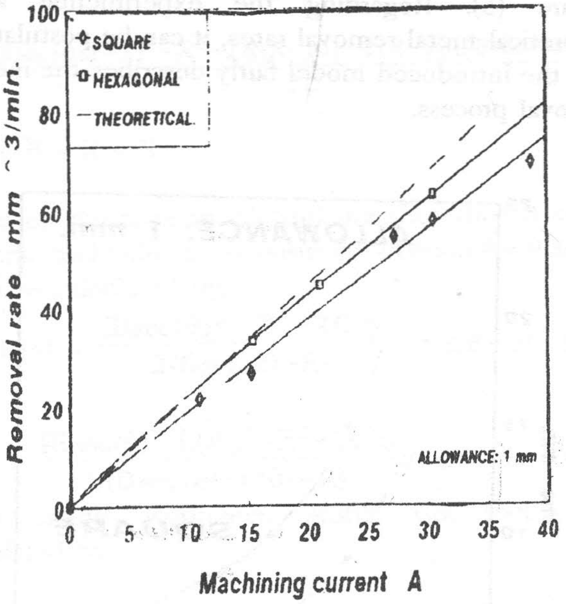


Figure 6. Effect of current on removal rate.

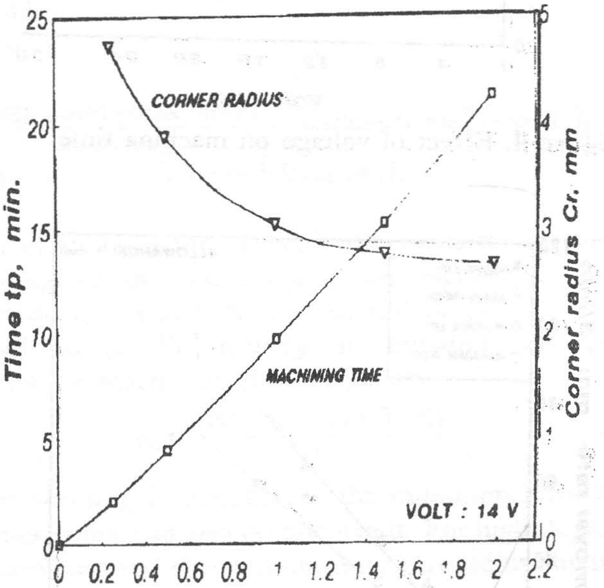


Figure 7. Effect of allowance on time & corner radius.

Figure (7) indicates the increase of the machining allowance results in a longer forming time and consequently the smaller will be the corner radius. The longer time is mainly related to the larger volume to be removed from the workpiece sides, at greater allowances. Additionally, the reduced corner radius can be understood with reference to equation 3. As can be seen from Figure (8), the decrease of the average machining current and the elongated machining time at larger allowance explains the falling trend of the metal removal rate. The experimental data fairly agree with the theoretical values especially at small machining allowances, probably due to the alteration of the electrolyte properties at elongated machining times.

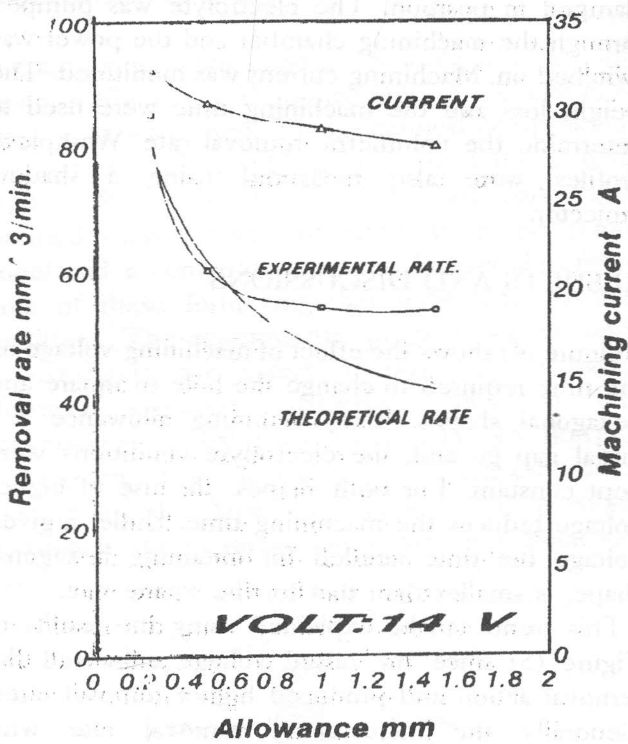


Figure 8. Effect of allowance on current & removal rate.

The effect of the number of sides on the removal rate and the forming time is shown in Figure (9). It is obvious that, for a given corner radius, voltage, etc. the increase of the number of sides raises the volumetric removal rate due to the increased number of active edge that reduces the machining time tp. Figure (10) shows the photograph of some machined workpieces and their experimental conditions while Figure (11) illustrates the measured and calculated workpiece profiles with respect to the cathodic tool designed for machining of the triangular and square shapes. However further work is to be carried out in order to shed more light on the accuracy of produced shapes by this method. This approach can also be extended for the production of elliptical holes, rectangular slots and unequal sided triangles. Tools for production of dies and molds, of any shape, can also be designed by dividing the entire profile to definite sections and calculating the corresponding tool profile for each one.

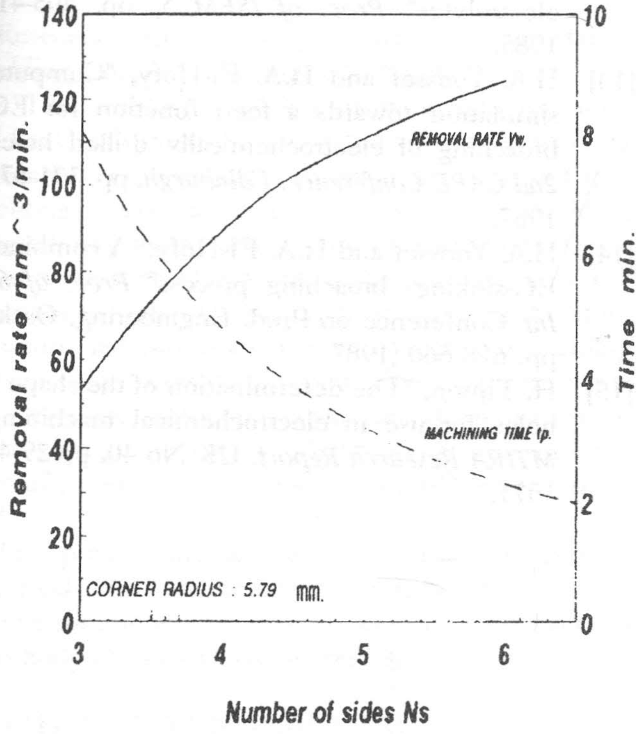


Figure 9. Effect of shape on removal rate & time.

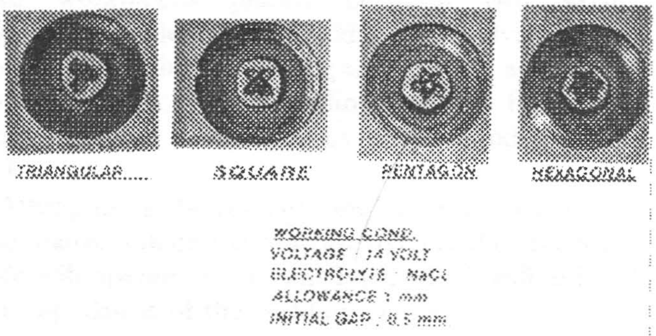


Figure 10. Workpiece forms produced.

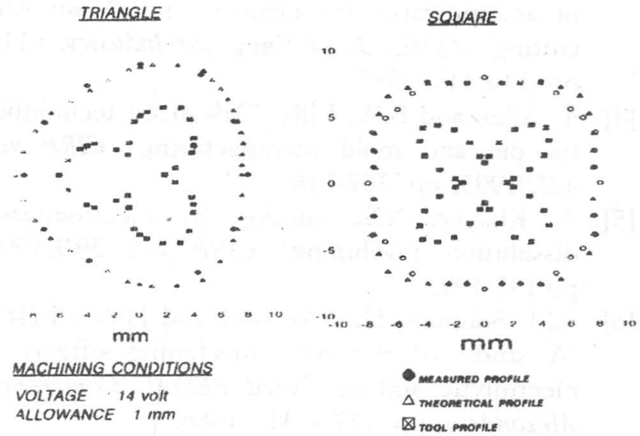


Figure 11. Workpiece and tool profiles.

CONCLUSIONS

From the theoretical model and the experimental work it can be concluded that

1- The use of higher voltage speeds up the machining process.
2- Under similar conditions, the increase of the machining allowance raises the machining time with consequent decrease of the corner radius.
3- The increase of shape sides raises the removal rate and reduces the machining time.
4- The model presented, fairly describes, the experimental situation especially at small machining allowance or shorter machining times.

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REFERENCES

[1] C.V. Kargin, "Electrochemical machining of shaped surfaces on round components by tubular shaped cathode tools " *Russian Engg. J.*, v. iv No, 11 pp. 64-68, 1975

[2] C.V. Kargin, "Electrochemical shaping using tubular section cathode tools" *Russian Engg. Journal*, v. iv No 4, pp. 73-74, 1975.

[3] H.A. El-Hofy and J.A. McGeough, "Evaluation

of an apparatus for electrochemical arc wire cutting" *ASME, J. of Engg. for Industry*, v110, pp. 110-117, 1987.

[4] T. Allen and B.W. Lilly, "Advanced techniques for die and mold manufacturing" *CIRP* vol. 42/2/1993, pp. 707-716.

[5] A. Khayry, "Die sinking by electroerosion dissolution machining" *CIRP* vol. 39/1/1990, pp.195-199.

[6] S.M. Soliman, H.A. Youssef and H.A. El-Hofy "A study of the side machining effects in electrolytic sinking " *3rd PEDAC Conference, Alexandria*, pp. 717 -732 , 1986.

[7] A.F. Rashed, H.A Youssef and H.A El-Hofy, "Effect of some process parameters on the side machining during electrolytic sinking" *3rd PEDAC Conference, Alexandria*, pp. 733-746, 1986.

[8] A.I. Loskutove, "Increasing the accuracy of electrochemical machining of holes" *Electrochem. Indust. Processing & Biol.* v. 3, pp. 32-34, 1980.

[9] J.A. McGeough, *Principles of Electrochemical Machining*, Chapman and Hall, London, 1974.

[10] V.K. Jain and P.C. Pandy, "Design and analysis of ECM tooling" *Precision Engineering*, pp. 199-206, 1974.

[11] E. Rumyantsev and A. Davydov, *Electrochemical Machining of Metals*, Mir publishers, Moscow, 1989.

[12] C. Hin-Min Zhu; C. Larsson and J. Bannard, "On the use of dilute solutions as ECM electrolytes" *Proc. of ISEM 5*, pp. 405-415 1985.

[13] H.A. Youssef and H.A. El-Hofy, "Computer simulation towards a feed function for EC-broaching of electrochemically drilled holes" *2nd CAPE Conference, Edinburgh*, pp. 371-375, 1987.

[14] H.A. Youssef and H.A. El-Hofy, "A combined EC-sinking- broaching process" *Proc. of 6th Int.* Conference on Prod. Engineering, Osaka, pp. 658-660 ,1987.

[15] H. Tipton, "The determination of the shape of holes for use in electrochemical machining" *MTIRA Research Report*, UK No 40, pp.29-42, 1971.