CHARACTERISTICS OF PULSE ELECTROCHEMICAL MACHINING

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ABSTRACT

The process of pulse electrochemical wire machining has been experimentally investigated under conditions of variable electrolyte flow velocity, and pulse characteristics such as pulse time, relaxation interval and current. The volumetric removal rate, cut width, surface roughness, current density and current efficiency have been assessed. Conditions leading to gap short circuiting are analytically determined.

Keywords: Pulse electrochemical machining, Conductivity, Gas bubbles, Velocity, Current efficiency, Current density, Shorting limit.

Nomenclature

A Atomic weight.
a Tool feed rate, mm/min.
α Duty cycle=to/(to + tr),%.
to Pulse duration, ms.
tr Relaxation time, ms.
C Material constant, $C = \varepsilon \kappa V e / F \rho$
τ pulse cycle time, ms.
F Faradays constant, 96500 C.
Ye Equilibrium gap, mm.
Y1 Minimum inter electrode gap, mm.
V Gap voltage, volt.
Ve Effective voltage, volt
Vsh Shorting voltage, volt.
u Electrolyte velocity, m/s.
ε Chemical equivalent, A/z
ρ Density of work material g/mm^3.
z Valence of work material
k Electrolyte conductivity, Ω^{-1} mm^{-1}.
λ Voltage/feed ratio, volt min./mm.

INTRODUCTION

Electrochemical machining (ECM) is a metal removal process that involves anodic dissolution of the workpiece material at high rate under conditions of rapid electrolyte flow and small inter electrode gap. ECM has many advantages such as the independence of the machining rate on hardness, the absence of tool wear and induced thermal stresses in the workpiece and the ability to produce high surface quality. The process is ideally suited to machining of complex shaped components made from high strength heat resistant alloys as typically found in aerospace and nuclear industries.

The introduction of pulsating voltage allows the application of extremely high instantaneous current density, to the anodic workpiece, without the need for an elaborate electrolyte pumping system and a rigid machine frame [1]. This is because each pulse is followed by a relaxation time of zero current which allows for the removal of the reaction products and heat generated by the joule effect from the inter electrode gap. The main object of using pulse currents in ECM is to improve the machining accuracy. Since the average current density in pulsed electrochemical machining (PECM) is usually much lower than that in dc current, the process is, therefore, limited to applications which do not require high machining rates. The results of reference [2] indicated that pulse duration has substantial effect on metal removal as compared to the effect of the machining voltage. Electrochemical wire cutting ECWC is an interesting application of PECM where due to, the small effective surface area of the cutting tool, inexpensive pulse generators and simple electrolyte pumping devices can be used. The process of (PECWC) finds typical applications in cutting of hard materials such as refractory crystals for metallurgical examination. It is also suitable for the production of intricate profiles for forging, pressure casting and extrusion processes. The problem of optimizing the pulse parameters in order to achieve maximum current density, before the instant of gap blocking using single pulse generator has been presented in reference [3]. In this regard it has been concluded that to speed up PECM, it is necessary to raise the pulse current.

A mathematical model for PECM process; using multiple pulses that takes into account the non-steady physical phenomena in the gap, has been considered by Rajurkar et al [4], considering the movement of the bubble-mixed electrolyte layer in the inter electrode gap. The machining characteristics including pulse current, removal rate, effective electrochemical equivalent and electrolyte conductivity variations have been analyzed based on the proposed model and experiments. Condition of the thickness of the bubble layer to equal the gap size (gap blocking) have been also determined. The work of Jain and Pandy [5] in ECWC was limited for a short machining time of few seconds without predicting the process accuracy. The simple analytical approach of Ghabrial et al [6] dealt with the problem of evaluation of the frontal inter electrode gap along the axis of the workpiece taking into account the effects of simultaneous variations in temperature, electrolyte conductivity, current density and other related parameters using the finite element technique. Chikamori and Ito [7] used pulsating current to study ECWC in stagnant electrolyte using 0.2 mm wire diameter at feed rate of 0.2 mm/min. during machining of carbon steel plate of 30 mm thickness.

This paper presents experimental and analytical work that shows the characteristics of pulse electrochemical wire cutting, at constant feed rate, and under variable electrolyte flow velocity, pulse time, pulse current and the relaxation time between successive pulses.

EXPERIMENTAL CONDITIONS

Linear cuts were achieved in hardened steel specimens of 6 mm thickness at a fixed cutting rate of 0.3 mm/min. $NaNO_3$ (20%) electrolyte was pumped, coaxial with the wire, through two nozzles set at two sides of the anodic workpiece. For nozzle flow rate of 6 l/min., the electrolyte inlet velocity, to the gap, was varied by changing the feeding distance for the two nozzles. A pulsed voltage of 95 volt was applied between the anodic workpiece and the cathodic wire electrode.

The pulse time was changed between 0.01-0.5 ms at a relaxation interval of 0.01 ms. For a given pulse time of 0.2 ms the relaxation time interval was between 0.01-0.25 ms. The energy available in each pulse was also varied by using the pulse current of 5-25 A. During each test both the average working voltage and current were measured and recorded. The volumetric removal rate was evaluated using the weight loss and the machining time. The resulting cut width were also measured using an x-y traveling microscope. For some specimens the surface roughness was also evaluated using a roughness meter. Finally the specific removal rate and hence the current efficiency were calculated on the basis of the average current and the volumetric removal rate.

RESULTS AND DISCUSSIONS

Figure (1) shows the time displacement diagram for both the cathodic tool electrode and the anodic workpiece. It can be seen that the minimum gap Y1 can be described by

$$Y1 = Ye - a\,(1 - \alpha)\tau \qquad (1)$$

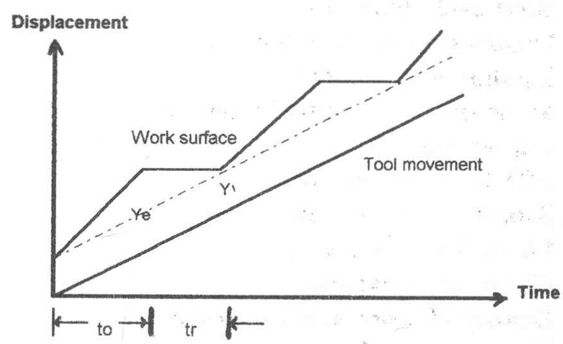

Figure 1. Tool and workpiece movement in PECM.

Shorting occurs when the value of Y1 becomes zero given that the voltage gradient is small enough to avoid breakdown that forms discharges and arcs which would lead to the transition of the machining process from ECM to the combined electrochemical -discharge machining. Such a combination is achieved at high voltages and narrow machining gaps associated with high feed rates [8].

Hence; the average shorting voltage Vsh, becomes

$$Vsh = a^2 F\rho\,(1 - \alpha)\,\tau/\kappa\,\epsilon \qquad (2)$$

The maximum possible speed can be calculated from

$$a_{max} = \sqrt{\frac{Ve\varepsilon\kappa}{F\rho(1-\alpha)\tau}} \qquad (3)$$

The ratio between the minimum voltage and maximum speed (λ) summarizes the conditions leading to gap short circuiting. The maximum pulse cycle time (τ_{max}) that causes shorting can also be given by:

$$\tau_{max} = \sqrt{\frac{Vsh(\varepsilon)\kappa}{a^2F\rho(1-\alpha)}} \qquad (4)$$

The minimum possible frequency, before the onset of gap short circuiting, f_{min} [9]

$$f_{min} = 1/\tau_{max} \qquad (5)$$

Effect of electrolyte flow velocity::

Figure (2) shows the increase of the volumetric removal rate, and cut width, with electrolyte flow velocity. Under such conditions proper electrolyte flushing of the machining products in the form of metal precipitates gas bubbles occurs. At low flow velocity, the percentage of gas bubbles and moreover the bubble size that fill the inter electrode gap is raised. Circumstantially, the gap resistance is greatly increased with consequent decrease of the machining current, its efficiency and hence the removal rate and width of cut. Figure (3) reflects the effect of flow velocity on flushing away the gas bubbles from the inter electrode gap on raising the current density, specific removal rate and moreover the current efficiency.

The increase of current efficiency and specific removal rate reflects the improvement in the dissolution process and hence the effective utilization of the machining current with flow velocity. In this regard, Rumyantsev and Davydove [10] reported that the manner in which the current varies, after a voltage pulse has been applied, depends on the electrolyte pressure. At low pressure, the fraction of the gap volume, filled with gas, plays a predetermined role and the current increases. At greater pressures, the gas bubbles become smaller in size, heat built-up plays a greater role as it raises the electrical conductivity, the current rise until a certain time and then decrease owing to the predetermined effect of gas content. The current density and hence the material removal rate has been reported to decrease with the rise in air-electrolyte ratio [11]. Moreover the resistivity of the interface between the electrode and electrolyte is strongly influenced by the velocity of the electrolyte and the current density [12-13].

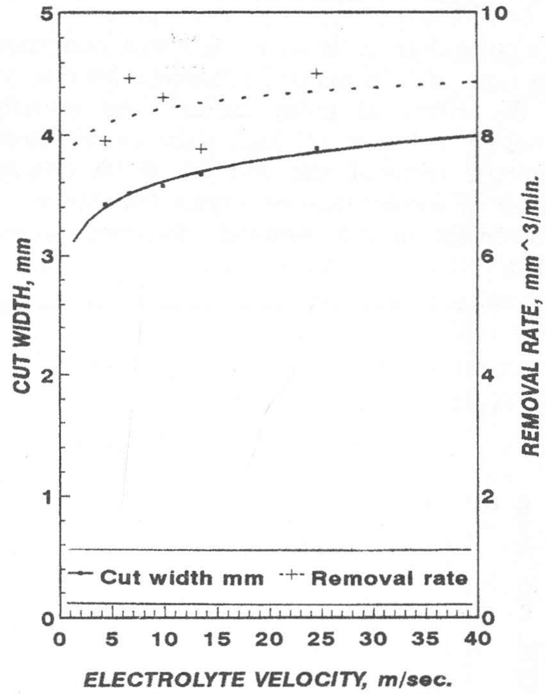

Figure 2. Effect of flow velocity on removal rate and cut width.

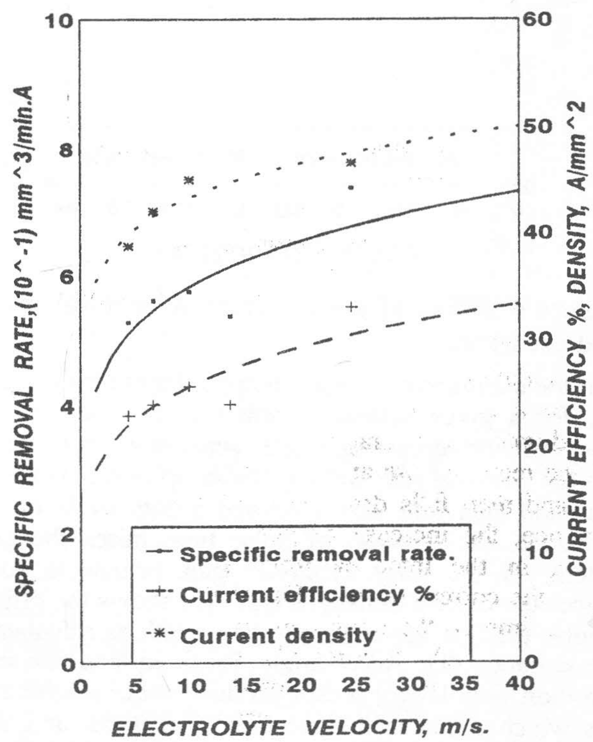

Figure 3. Effect of flow velocity on current density and efficiency.

Effect of pulse characteristics:

For pulse duty cycle of 93 % which corresponds to pulse time of 0.16 ms and relaxation interval of 0.01 ms, the effect of pulse current was investigated. According to Figure (4) high pulse current raises the volumetric removal rate and cut width through the increase of current density. Figure (5) shows also the improvement in the removal efficiency with pulse current.

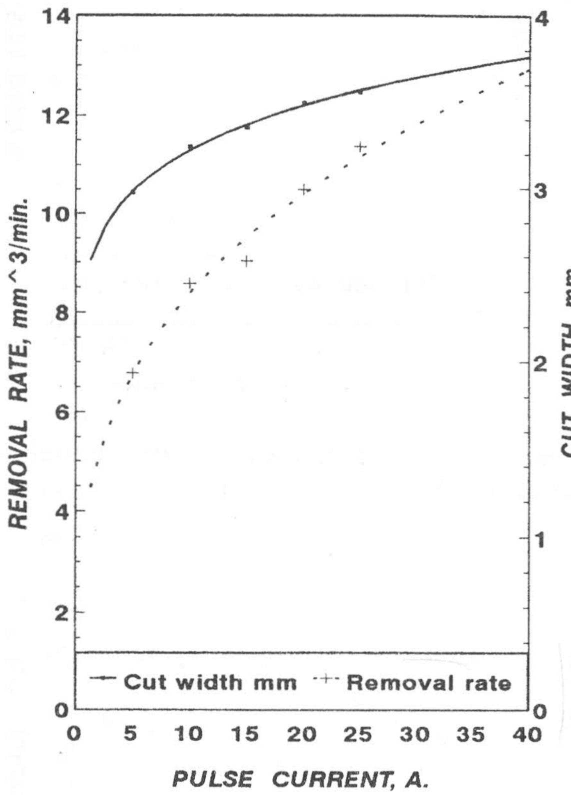

Figure 4. Effect of pulse current on removal rate and cut width.

For the cutting speed experimented, Figure (6) reveals that, for a given relaxation interval, the increase of pulse duration encourages gas generation that raises both the removal rate and cut width up to a maximum value and then falls down beyond a duty cycle of 90 %. Hence, the increase of pulse time raises the gas content, in the inter electrode gap, which in turn reduces the current density. Figure (7) shows the effect of pulse time on the minimum gap width as calculated from equation (1). .Accordingly, for fixed feed rate and relaxation time longer pulses produce wider machining gaps which explains the increased cut width and the decreased current density shown, respectively, in Figures (6,8).

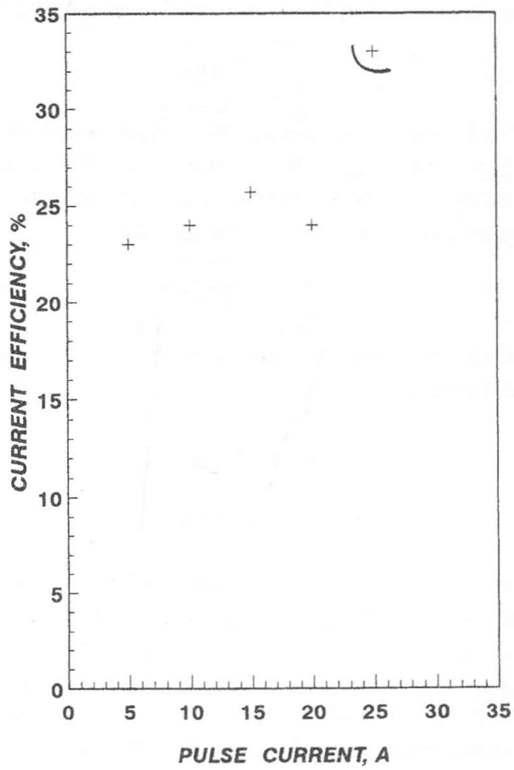

Figure 5. Effect of pulse current on current efficiency.

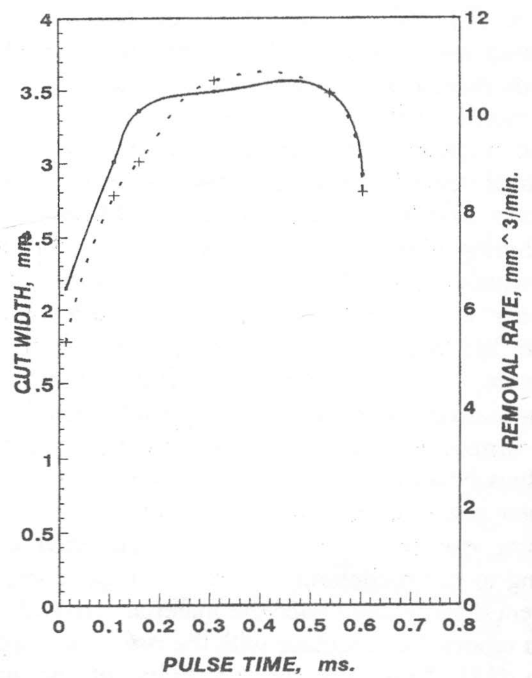

Figure 6. Variation of removal rate and cut width pulse time.

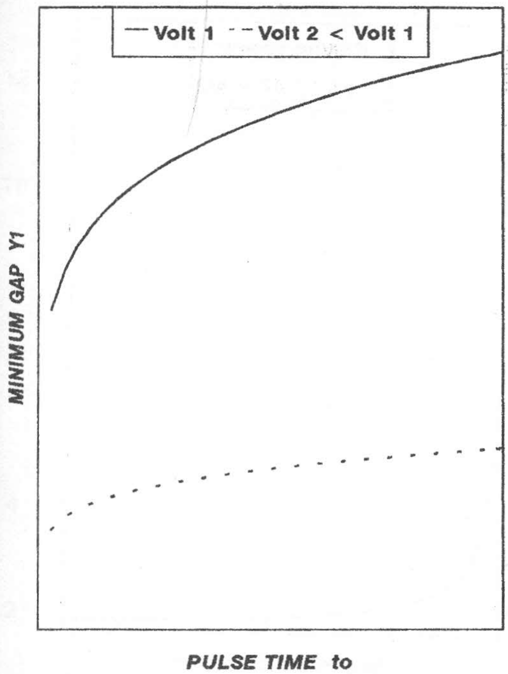

Figure 7. Effect of pulse time and gap voltage on the minimum gap.

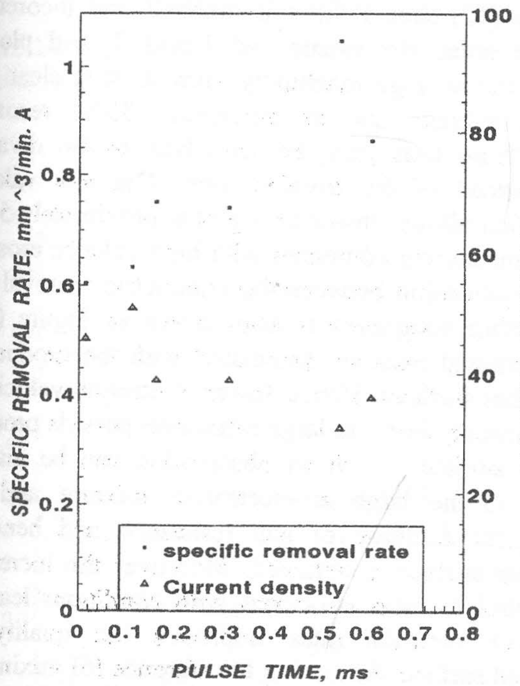

Figure 8. Effect of pulse time on specific removal rate and current density.

At the longest pulses tested the gas content is greatly increased, gap blocking is expected to prevail and the difficulty of gap recovery during the relaxation time arise. Consequently a decrease in removal rate and cut width achieve.

Figure (8) shows similar trend with respect to the specific removal rate. The drop of current efficiency with air ratio has been also reported by Ghabrial et al [6] because as the air increased the mixture changed from bubbly flow to a mist type flow. Furthermore, Saushkin et al [14] suggested a certain frequency below which pulsed ECM takes place under given conditions. The increase of inlet pressure leads to higher values of that critical frequency.

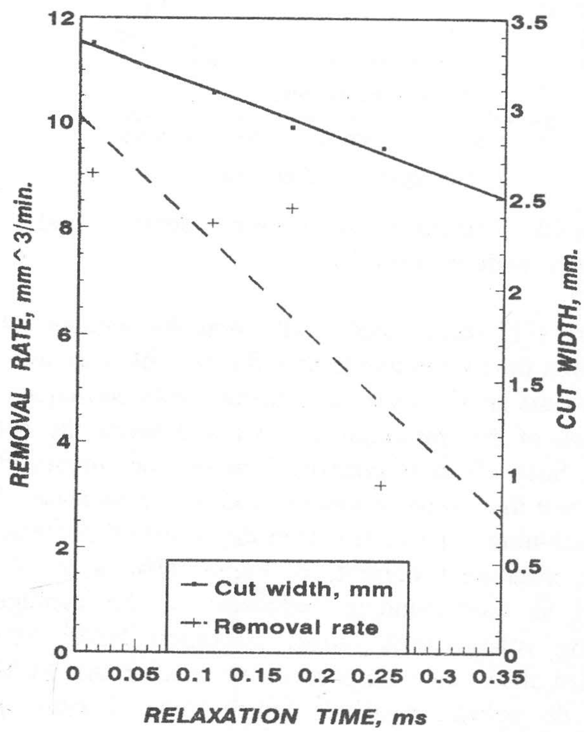

Figure 9. Effect of pulse relaxation time on removal rate and cut width.

For a given electrolyte flow velocity, pulse duration and current, Figure (9) shows the effect of pulse relaxation time on both the volumetric removal rate and width of cut. The increase of interval between successive pulses reduces the effective gap voltage, Ve, machining current, Figure (10), removal rate and finally the cut width that improves the process accuracy.

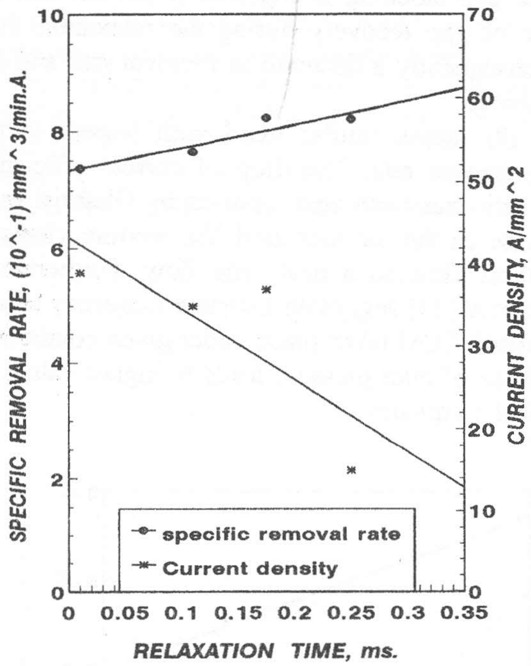

Figure 10. Variation of current density and efficiency with relaxation time.

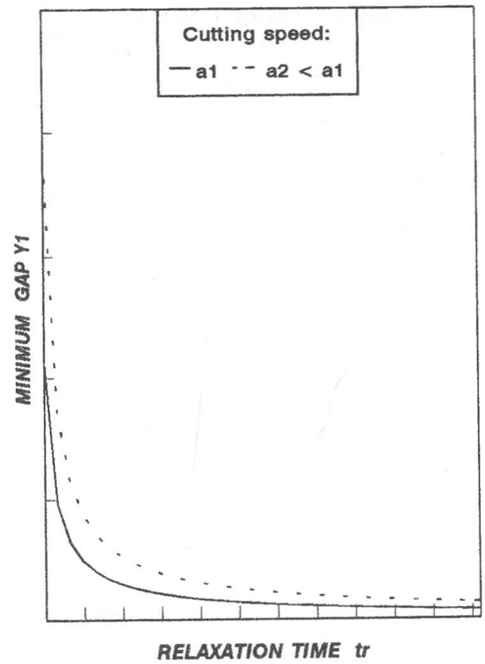

Figure 11. Effect of relaxation time and feed on the minimum gap.

Figure (11) shows analytically that the increase of relaxation time gives ample time for the tool to advance towards the anodic workpiece surface with consequent decrease of the minimum gap Y1 and hence the cut width. *Such effect is intensified as the tool moves at faster rate that would normally lead to the increase of* the machining current. However the observed decrease of the machining current, in Figure (10) is mainly related to corresponding reduction of the average working voltage with longer relaxation times. The obtained observation supports the postulation that ECM using dc voltage produces larger removal rates in addition to wider cuts, at zero relaxation time. Regarding the effect of relaxation interval on the specific removal rate, Figure (10), it can be postulated that for the constant cutting rate experimented, small relaxation time raises the overall machining current density which, in turn enhances the process of gas generation that deteriorates the specific removal efficiency. On the other hand the increase of current efficiency with pulse relaxation time reflects that the current density decreases at a larger rate (20 A/0.25 ms) while that for the removal rate is around 1.5 mm^3/0.25 ms.

Figure (12) shows the experimental and theoretical removal rates, for valence of 2 and 3. and plotted against the average machining current. It is clear that for the average current efficiency (33%) recorded *during these tests iron, Fe, dissolves in the divalent state instead of the trivalent one. The low valence* dissolution allows power saving of approximately 57 % during machining compared with high valence erosion.

The relationship between the volumetric removal rate and surface roughness is also shown in Figure (13). High removal rates are associated with the production of rougher surfaces. Hence, lower electrolyte velocities, pulse current, time and large relaxation periods produce smooth surfaces. Such an observation can be mainly related to the large air-electrolyte mixture and the consequent decrease of gap resistance and hence a smoother surface is obtained. Moreover the increased air-electrolyte ratio associated with conditions leading to lower removal rates improves the quality of produced surface. According to reference [6] mixing air with electrolyte proved to increase both the accuracy and surface finish.

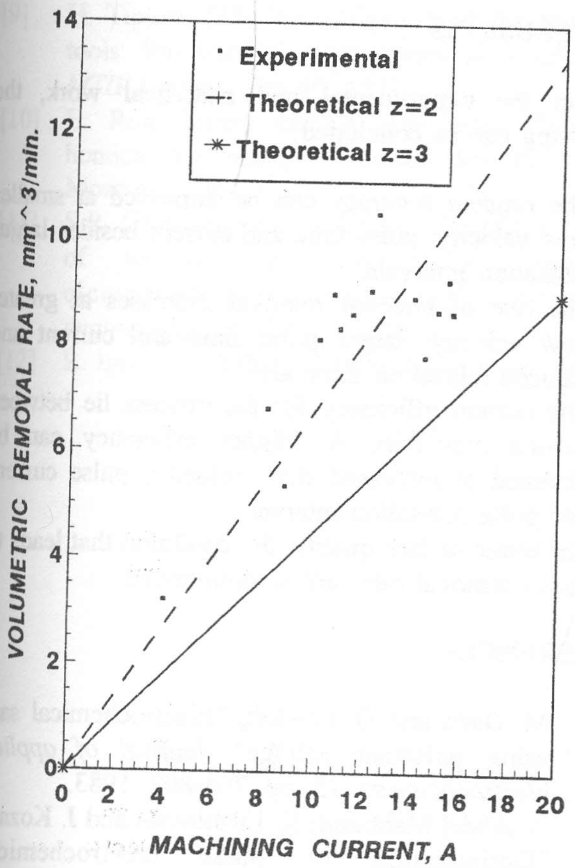

Figure 12. Relationship between machining current and removal rate.

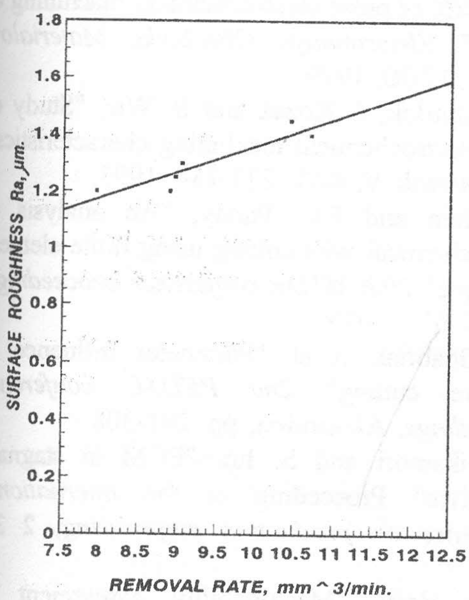

Figure 13. Relationship between removal rate and surface roughness.

The general decrease of current efficiency with increasing current density is shown in Figure (14). The small content of the gas bubbles, in the gap, at smaller current density enhances the dissolution process and hence increases the current efficiency.

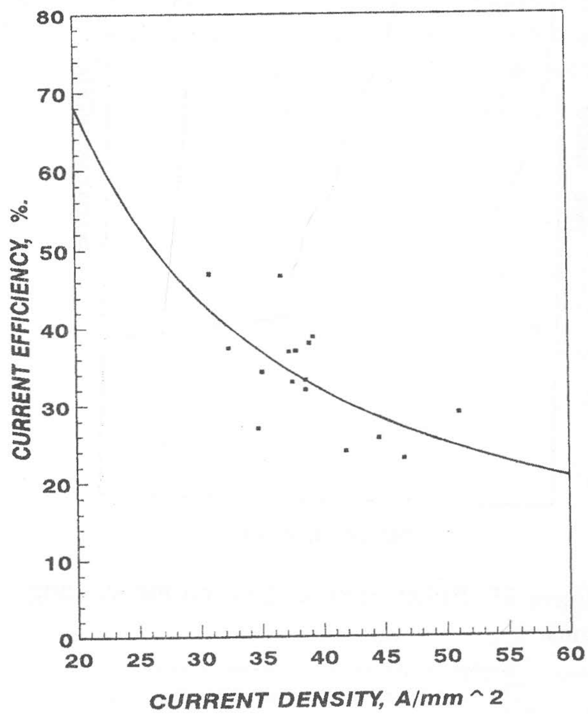

Figure 14. Effect of current density current efficiency.

Shorting limits:

Following the tool workpiece kinematics, Figure (1), and the assumptions of Tipton [9], Figure (15) indicates that for constant relaxation time, the increase of pulse duration makes short circuit liable to occur at longer pulse cycle times (smaller frequencies). Moreover the decrease of λ, with pulse time, reflects also that gap shorting occurs at smaller gap voltages as well as larger tool feed rates. The shorting phenomenon is found to be more sensitive to the tool feed than the gap voltage.

The effect of relaxation time on the shorting conditions is shown in Figure (16). At longer relaxation periods shorting becomes ready to occur at larger gap voltages as well as smaller cutting speeds. Shorting is more dependent on the gap voltage than the feed rate. The same figure also shows that shorting is found to be evident at smaller cycle times or greater frequencies.

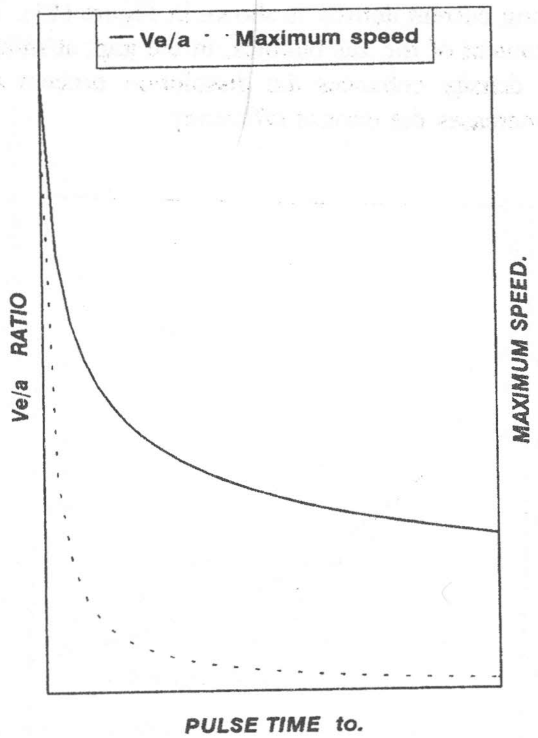

Figure 15. Effect of pulse time on the shorting limits.

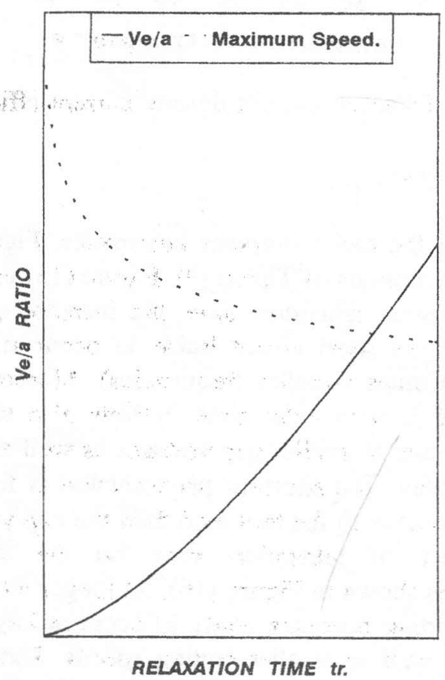

Figure 16. Effect of relaxation time on the shorting limits.

CONCLUSIONS

From the experimental and analytical work, the following can be concluded;

1- The process accuracy can be improved at smaller flow velocity; pulse time and current besides larger relaxation intervals.
2- The rate of material removal increases at greater flow velocity, larger pulse time and current and reduced relaxation intervals.
3- The current efficiency for the process lie between 0.4-0.8 mm^3/min. A. Higher efficiency can be obtained at increased flow velocity, pulse current and pulse relaxation interval.
4- For better surface quality, the condition that leads to larger removal rates are recommended.

REFERENCES

[1] M. Datta and D. Landolt, "Electrochemical saw using pulsating voltage" *Journal of applied electrochemistry* 13, pp. 795-802, 1983.

[2] A. Abdel Mahboud; K. Luskowski and J. Kozak, "Optimization of pulse electrochemical machining parameters" *Fourth PEDAC conference*, Alexandria, pp, 371-380, 1989.

[3] A.V. Pybalco and G.N. Zaydman, "The energy possibility of pulse electrochemical machining of metals." *Electronnaya Obrabotka Materialov*, V4, pp. 17-20, 1979.

[4] K.P. Rajurkar, J. Kozak and B. Wie, "Study of pulse electrochemical machining characteristics" *CIRP Annals* V, 42/1, 231-234, 1993.

[5] V.K. Jain and P.C. Pandy, "An analysis of electrochemical wire cutting using finite element technique" *20th MTDR conference proceedings*, pp. 631-635, 1979.

[6] S.R. Ghabrial, et al. "Parameter influence in EC-wire cutting" *2nd PEDAC conference proceedings*, Alexandria, pp. 291-308

[7] K. Chikamori and S. Ito, "ECM in stagnant electrolyte" Proceeding of the *international conference on production engineering*, 2 31, 1977.

[8] H. El Hofy, "Machinability assessment in EEDM" *Alexandria Engg Journal*, January, 1996.

[9] H. Tipton, "The determination of the shape of tools for use in electrochemical machining" *MTIRA report*, No 40, 1971.

[10] E. Rumyantsev and A. Davydov, "Electrochemical machining of metals" *Mir publishers*, Moscow, 1989.

[11] S.R. Ghabrial, and S.J. Ebeid, "Beneficial effects of air-electrolyte mixture in stationary electrochemical machining" *Precision engineering*, pp. 221-223, 1981.

[12] R. Ippolito, "Effect of fluid dynamic conditions on the gap resistivity in EDM." *CIRP Annals* 24/1, pp. 115-119, 1975.

[13] P.J. Moire and S.J. Harvey, "Some Effects of electrolyte flow rates on electrochemical machining process" *16 MTDR conference proceedings*, pp. 275-281, 1975.

[14] B. Saushkin, et al "Special features of the combined electrochemical and electroerosion of elongate m/c parts "*Electrochem. in Indust. & biol.*, V 105, part 3, 1982, pp. 8-14.