EFFECT OF WIRE SPEED AND MACHINING RATE ON GAP PHENOMENON AND SURFACE INTEGRITY IN EEDM

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ABSTRACT

This paper presents an experimental investigation into the role of wire winding speed and machining rate on the performance of electroerosion dissolution machining. An explanation to the material removal efficiency, surface integrity (accuracy and surface finish) and; the specific wire consumption has been provided. The inter-electrode gap phenomenon has been related to the ignition delay time, voltage gradient, machining phases and stability. A first order stochastic differential equation has been developed, from machined surface profile measurements, and used to define surface topography indices such as the characteristic crater depth and volume. Such indices are related to the machining rate and wire speed and their corresponding gap condition.

Keywords: Wire winding speed, EEDM, Gap phenomenon, Surface integrity autoregressive, Model, Surface roughness.

INTRODUCTION

Electroerosion dissolution wire cutting EEDWC is a novel process that found many industrial applications in the field of die and mold production. The process utilizes a thin wire electrode and machining occurs due to a major thermal erosion phase and a minor dissolution action. Such a combination increased the process productivity and improved the resultant surface quality [1]. The process has found further applications in machining composite materials using NaOH electrolyte [2], quartz and glass plates [3]. The metal removal process is enhanced by the sparking action and not by the arcing one because the later usually results in a low and localized material removal rate and yields more irregular machined surfaces. Under such circumstances the process was termed as the electrochemical spark machining ECSM by Jain et al [2].

EEDWC is affected by many variables that control its performance, accuracy and surface quality. Among these are the electrical parameters such as pulse time, relaxation interval and pulse current. Workpiece characteristics such as the melting point, thermal conductivity and specific heat has been dealt with [4-5]. No work has been undertaken to explain the process characteristics under varying wire winding speed. In EDWC, however, Kinoshita [6] studied the mechanical behavior of the wire electrode over a wide range of machining conditions. Smolentsev et al [7] determined the minimum wire tension and speed that would secure stable machining. He concluded that the relative wire consumption depends on the workpiece thickness and wire speed. Furthermore, the minimum wire speed and tension have been found to depend on the wire electrode diameter. Additionally a recommended wire speed should lie between 0.7-0.8 m/min. Recently Lou [8] used a wire speed in the range of 3-14 m/s and high input pulse energy for maintaining a stable and fast cutting in wire EDM.

Conditions leading to a reduced wire electrode vibration have been also reported by Taramykin [9]. The dependence of the maximum machining speed on wire tension has been reported in references [10-11]. During EEDWC the traveling speed of wire must be controlled so that the electrode wear is not exceedingly high and does not involve any danger of electrode destruction. In order to achieve this ultimate goal, the role of wire speed on the process behavior, produced accuracy, wire consumption coefficient and machining stability must be firstly clarified. Empirical relations relating the wire speed to the maximum cutting rate and the specific wire consumption factor were also derived. These equations assist the production engineer in choosing optimum machining conditions. The complex and stochastic nature of EEDM have been reported by Khairy [12]. The surface produced was, therefore, considered as representing the randomness inherent in the erosion-dissolution phenomena. The data dependent system, DDS, analysis, of the surface profiles, has been adopted for surface analysis in EDM [13] and EEDM [14]. Such a methodology has led, not only to its comprehensive topographical characteristics, but also to a better understanding of EDM and EEDM process behavior.

EXPERIMENTAL PROCEDURE AND CONDITIONS

The experimental set-up consists of electric power source that supplies square pulses of current, 15 A, duration 0.16 ms and interval of 0.01 ms. A stepper motor is used for the workpiece feeding mechanism. The wire traveling speed was selected to cover a wide range from the small value of 0.2 m/min. which is near to machining with a stationary electrode up to a high value of 2 m/min. NaNO3 electrolyte (20 %) was supplied to the machining gap at a velocity of 24.6 m/s through two coaxial nozzles.

Linear cuts of 10 mm length were achieved in 6 mm thickness steel plates. For each wire speed experimented the linear workpiece feed rate was increased in steps of 0.3 mm/min. up to the point of complete gap short-circuiting that terminated the machining progress. The product of the maximum possible speed and workpiece thickness is assumed to determine the process efficiency in mm^2/min. Each experiment were performed for a duration time of 3-25 min. depending on the workpiece moving rate. During each test, the machining current and voltage were recorded and hence the average ignition delay, machining phases, voltage gradient across the gap were calculated. After machining, the workpieces were cleaned, dried and reweighed to determine the volumetric removal rate, current and energy efficiencies. The relative wire consumption factor, in terms of the volume of wire used to remove a specific workpiece volume was also calculated and empirically related to the wire traveling speed and the process efficiency. The cut width was also measured using a Tool Maker's Microscope. Surface roughness profiles were also measured using a Tlysurf -4 stylus instrument. The roughens profiles digitized for further analysis and modeling as shown in the Appendix [14].

RESULTS AND DISCUSSIONS

Figure (1) shows that the removal rate increases with feed rate up to a certain level and then decays. The removal rate reaches maximum level at workpiece feed rate of 2.1 mm/min., when the wire speed is 0.2 m/min. Such maximal occurs at 3.3 mm/min. at a wire speed of 2 m/min. The increased removal rate is achieved, to the highest degree, as a result of substantial reduction of energy losses and the increase in the part, of energy, released in the discharge channel at optimum gap size.

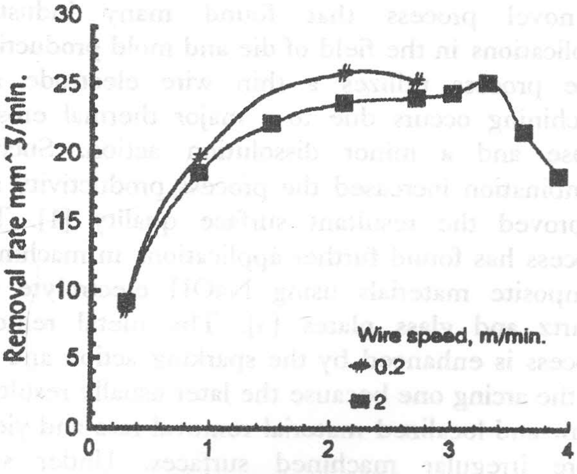

Figure 1. Effect of wire speed and machining rate on volumetric removal rate.

The increase of wire speed helps in flushing away the machining products from the inter-electrode gap and hence optimum gap conditions are obtainable as the machining rate increases. At a given machining rate, the increase of wire winding speed reduces the volumetric removal rate. Similar observations can also be seen with respect to the specific removal rate, Figure (2). Additionally, the energy utilization index is markedly affected by the machining rate and much less affected by the wire speed, Figure (3).

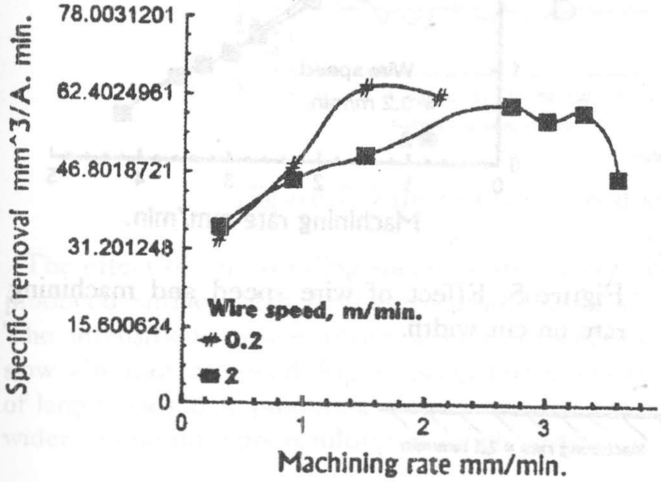

Figure 2. Variation of specific removal rate with wire speed and machining rate.

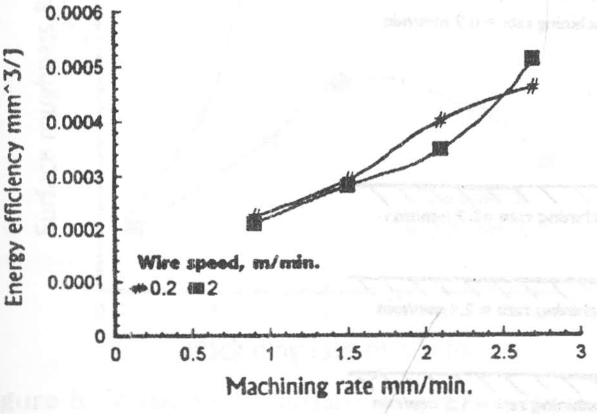

Figure 3. Effect of wire speed and machining rate on the energy efficiency.

During EEDM, the volumetric removal rate is achieved through the contribution of both the dissolution phase and the main erosion action of pulses. Figure (4) depicts that the erosion ratio is enhanced at the smaller wire winding speed which justifies the rise of volumetric removal rate. Under such circumstances, the ignition delay time decreases as a result of the high concentration of impurities that fill the inter-electrode gap, by the intensified erosion phase and the stagnation of the machining products in the gap as the wire moves slowly across the machining zone. During EDM, the increase in particles in the inter-electrode gap is known to raise the local field strength and current density thus, leading to the reduction of the ignition delay [15]. Moreover, the decrease of ignition delay with the concern of suspension has been also reported in reference [16]. The nature and extend of ignition delay dictate the changes in the types of discharges and the energy of each discharge which is related to the erosion rate and other technological parameters. Close monitoring of the ignition delay time provided the basis of the adaptive control system used for EDM [15]. Furthermore, the breakdown characteristics of EDM dielectric improved with the presence of impurities, thus resulting in higher removal rates. However, a too high level of impurity concentration increases the incidence of micro-short circuiting, thus leading to lower machining rates [5,15].

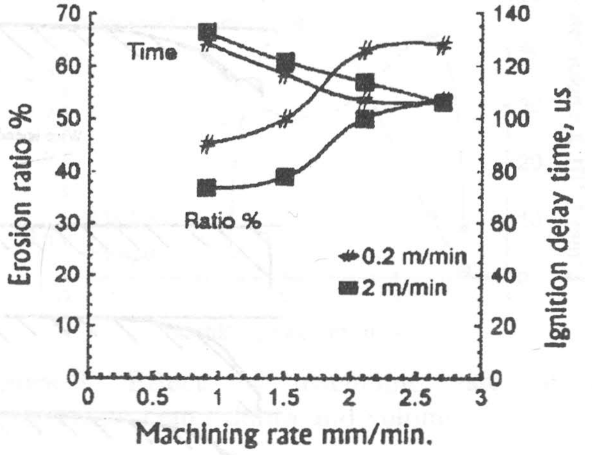

Figure 4. Variation of ignition delay time and erosion ratio with wire speed and machining rate.

For a given machining rate, the increase of removal rate, at low wire winding speed, is associated with the production of wider machining cuts, Figure (5). The same figure also depicts that at constant wire speed, the cut width decreases at greater machining rates despite the increased volumetric removal rate shown in Fig (1). Figure (6) illustrates the sharpness of the slot entrance at the different machining rates and wire speeds. Accordingly, one could conclude that the edge sharpness improves and the cut width decreases which reflects the a higher level of process accuracy at larger wire winding speeds and machining rates.

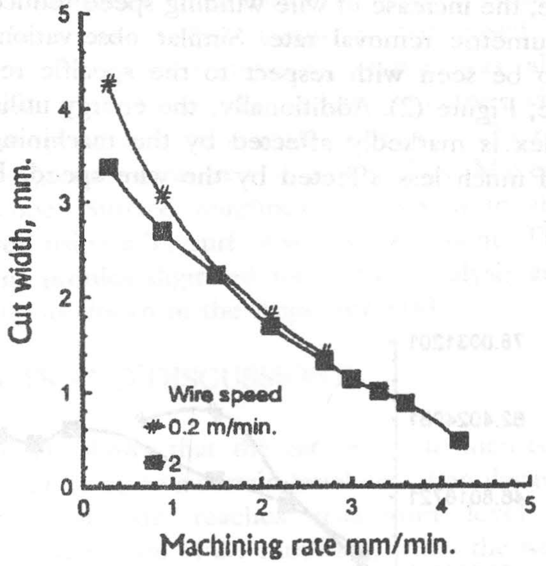

Figure 5. Effect of wire speed and machining rate on cut width.

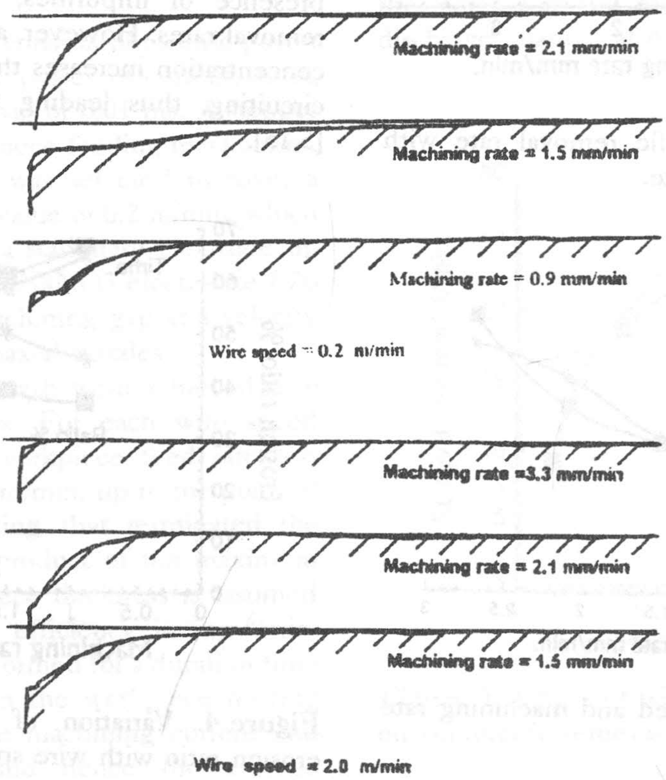

Figure 6. Cut entrance sharpness at different machining rates and wire speed.

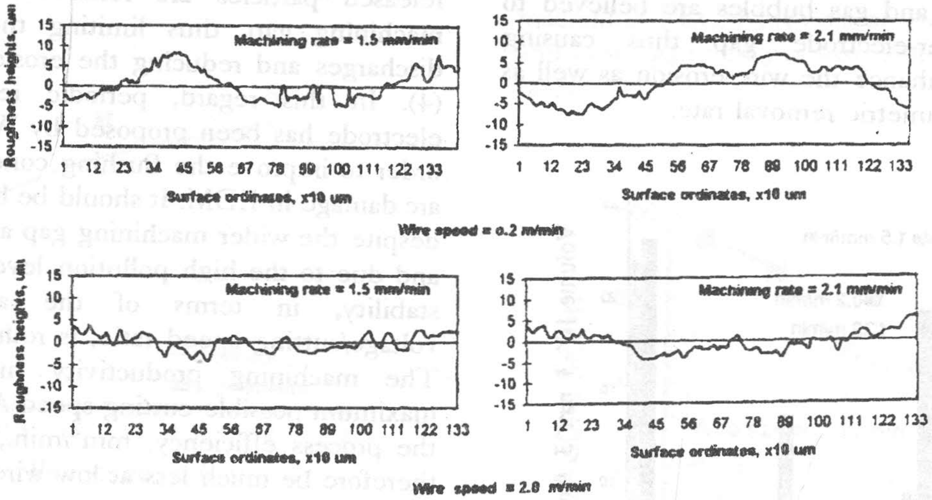

Figure 7. Effect of wire speed and machining rates on surface profiles.

The effect of wire winding speed on the quality of produced surfaces can be observed in Figure (7). The intensified erosion phase associated with the slow wire moving speed, Figure (4) generates craters of larger sizes that produces, greater removal rates, wider machining cuts resulting in rough surfaces.

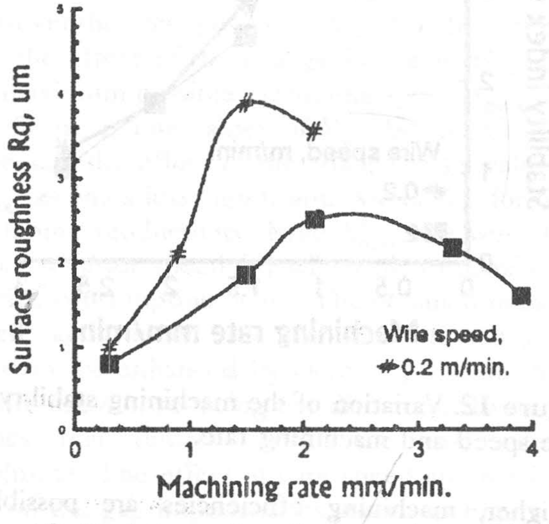

Figure 8. Variation of surface roughness Rq with wire speed and machining rate.

Figure (8) shows the effect of machining rate on the Rq roughness value. It is obvious that, Rq increases with machining rate up to a certain value beyond which it starts to fall. The same figure also illustrates the reduction in roughness value Rq at larger wire speeds. Such observations are in agreement with crater indices obtained from the stochastic modeling of the surface profile such as crater depth Figures. (9). As can be seen from Figure (10), the increase of crater depth, surface roughness Rq , the crater volume and, removal rate, at low wire speeds, are related to the intensity of the machining phases of Figure (4).

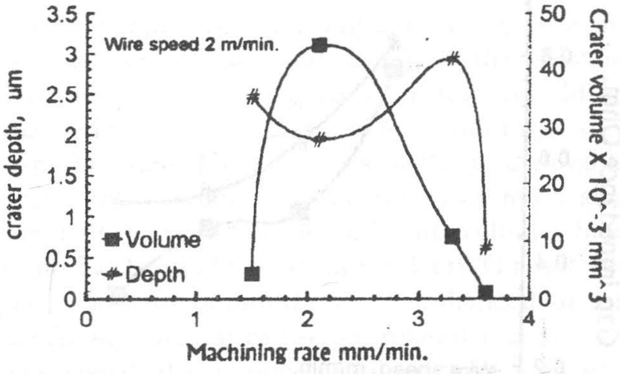

Figure 9. Effect of machining rate of the characteristic crater depth and volume.

The presence of wider machining gap at reduced wire winding speeds raises the inter-electrode gap impedance despite the high contamination of impurities, Figure (11). The larger gap impedance could also be related to the reduced wire diameter by the erosive action of sparks that forms severe craters in the slow moving wire electrode. The metallic particles and gas bubbles are believed to bridge the inter-electrode gap thus causing discharges that enhance the wire erosion as well as the increased volumetric removal rate.

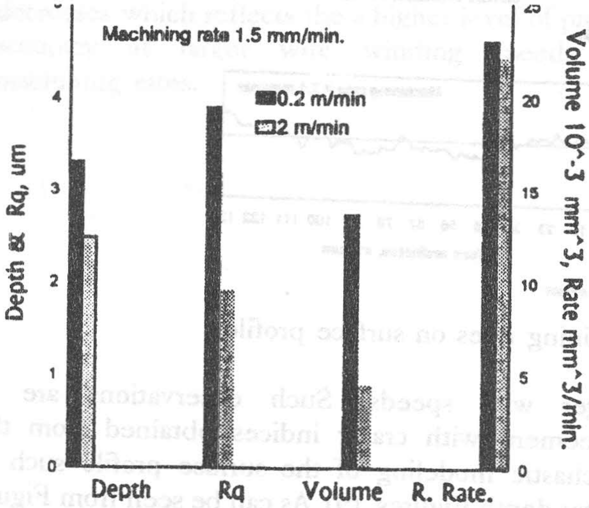

Figure 10. Variation of characteristic crater depth, roughness Rq, crater volume and the removal rate with wire speed.

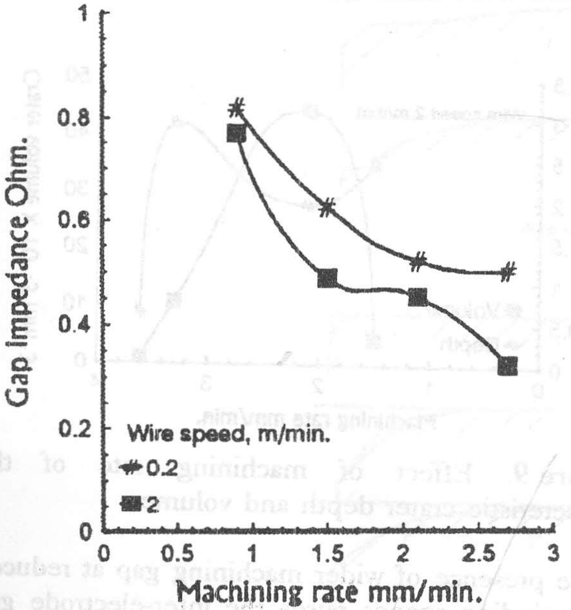

Figure 11. Effect of wire speed and machining rate on the gap impedance.

At larger wire traveling speed, such deposits and released particles are removed away, from the machining gap, thus limiting the occurrence of discharges and reducing the erosion phase, Figure (4). In this regard, periodic retraction of tool electrode has been proposed by Wang et al [17] in order to improve the flushing conditions and avoid arc damage in EDM. It should be born in mind that, despite the wider machining gap at low wire speed, and due to the high pollution level, the machining stability, in terms of the average working voltage/cutting speed ratio, is reduced Figure (12). The machining productivity measured by the maximum possible cutting speed A_{max}, mm/min., or the process efficiency, mm^2/min., Figure (13) will therefore be much less at low wire speeds.

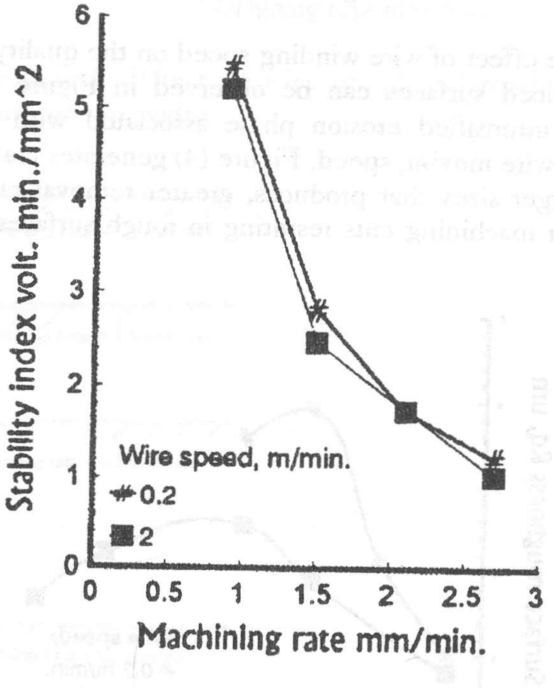

Figure 12. Variation of the machining stability with wire speed and machining rate.

Higher, machining efficiencies are possible in EEDM than those normally obtained during wire EDM [7] due to the combined effect of erosion-dissolution phase. Using the experimental data of Figure (13), the maximum possible speed A_{max} in terms of the workpiece thickness, W, and wire speed, V_w, can be estimated empirically by:

$$A_{max} = 21.6\ V_w^{0.1918}/W \qquad (1)$$

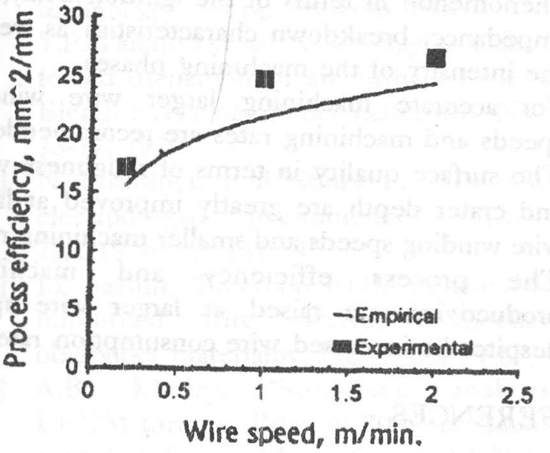

Figure 13. Effect of wire speed on the process efficiency.

Despite the limited number of data points available, the empirical formula fairly describes the experimental results and agree well with the findings of other research workers [7]. Accordingly, for cutting thicker workpieces the wire speed should be increased to achieve the same maximum speed obtainable when machining thinner ones. However,the low power of V_w (0.1918), indicates that the effect of the change in the wire speed on the maximum possible machining speed A_{max} will be significant at low values of V_w. As the wire speed increases, the effect of the change in its value over A_{max} becomes less significant. Moreover, for higher machining productivity, large A_{max}, the wire should travel at faster speed [8] which, in turn, raises the specific consumption factor. The obtained maximum speed and hence the process efficiency can, however, be enhanced by increasing the magnitude of wire tension, reducing the distance between wire guides that directly affect the wire vibration amplitude. The effect of wire speed and machining rate on the gap impedance is shown in Figure (11). The wider machining gaps and possibly the wire erosion may be responsible for the obtained trend. Under such conditions, the average voltage and hence the voltage gradient increase, Figure (14). Such machining conditions are favorable for the dissolution process to prevail, but due to the high concentration of impurities, the discharging process is dominating. High intensity sparks occur, at higher cutting rates, while pulsed electrochemical machining PECM prevails at wider machining gaps and lower gap voltages associated with slow cutting rates.

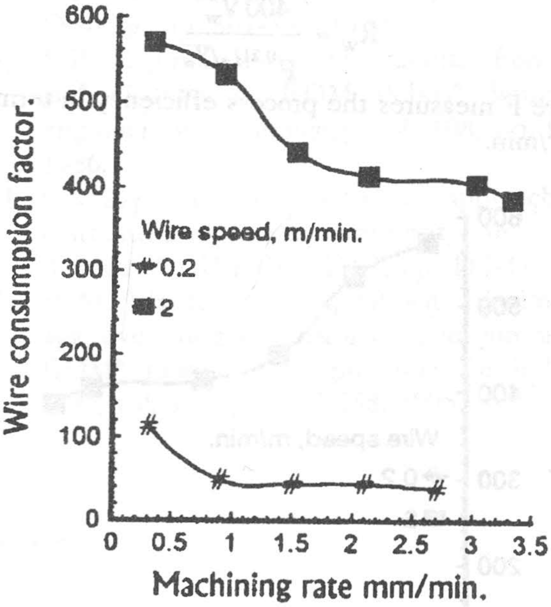

Figure 14. Effect of wire speed and machining rate on the voltage gradient.

The specific wire consumption factor, in terms of the volume of wire used to that of the workpiece, Rw, is shown in Figure (15) for the different machining rates and wire winding speeds experimented. Higher values of Rw is achievable at larger wire speeds due to the decreased removal rate, Figure (1) and the increased wire volume. Similar trend has been obtained during EDWC in reference [7]. Since the removal rate is enhanced at faster machining rates, it can be postulated that at a given wire speed, the increase of cutting rate reduces the relative wire consumption factor Rw. Such a reduction is preferable from the economical point of view despite the decrease of process efficiency at low wire traveling speed. However the large decrease of wire speed that is associated with the active erosion phase would limit the use of such small speeds. Under such conditions and for a given wire tension, the wire cross section could be reduced causing wire breakage and disruption of the machining process. In modern EDWC machines both the wire speed and tension are automatically adjusted by the machine in order to avoid wire breakage during machining. The relative wire consumption factor R_w can be empirically expressed by the following equation;

$$R_w = \frac{400 V_w^{0.7}}{F^{0.21/.\sqrt{V_w}}} \qquad (2)$$

where F measures the process efficiency in terms of mm^2/min.

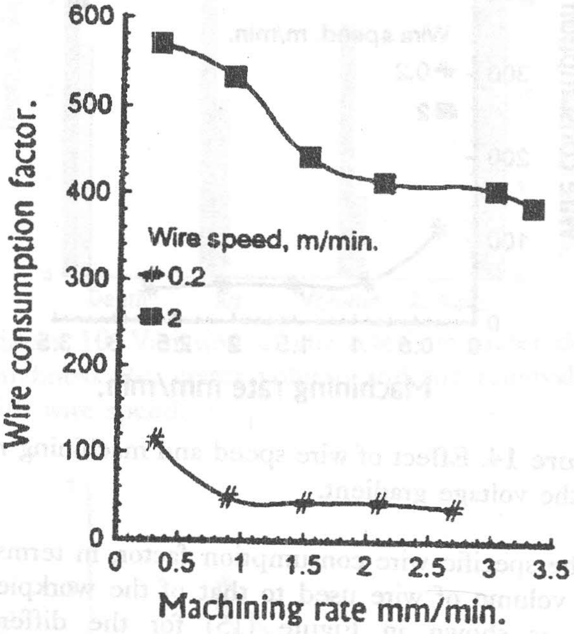

Figure 15. Variation of wire consumption factor with machining rate and wire speed.

It can, therefore, be concluded that, for a given wire speed, the increase of cutting speed, mm/min., and workpiece thickness, mm, reduces the specific wire factor. Additionally, the same wire consumption could be achieved by raising the wire speed in accordance with F.

CONCLUSIONS

From the experimental work undertaken with respect to the effect of wire winding speed at different machining speeds, and for the range of factors considered here, the following can be concluded:

1- The wire winding speed affects the gap phenomenon in terms of the ignition delay, gap impedance, breakdown characteristics as well as the intensity of the machining phases.

2- For accurate machining larger wire winding speeds and machining rates are recommended.

3- The surface quality in terms of roughness value and crater depth are greatly improved at larger wire winding speeds and smaller machining rates.

4- The process efficiency and machining productivity, are raised at larger wire speed despite the increased wire consumption rate.

REFERENCES

[1] H. El-Hofy and A. Khairy, "A comparative study on produced geometry and surface integrity by electrochemical machining, electrodischarge machining, and electroerosion dissolution machining" Proceedings of IEMS 5, University of Central Florida, March, 1995.

[2] V.K. Jain, et al "Experimental investigation into traveling wire electrochemispark machining (TW-ECSM) of composites" Journal of Engineering for industry, vol. 113, pp. 75-84, 1991

[3] V. Rajurkar, et al "Effect of circuit parameters on the electrolytes in electrochemical discharge phenomenon" Journal of material processing technology, 52, pp. 301-318, 1995.

[4] H. El-Hofy, "Assessment of machinability in electroerosion dissolution machining" Alexandria Engineering Journal (AEJ) vol. 35 No. 2, January, pp 43-49, 1996.

[5] H. El-Hofy and J. McGeough, "Effect of pulse duty cycle on stock removal rate and accuracy in ECDM" PEDAC-4, Alexandria, Dec., pp. 355-362, 1989.

[6] N. Kinoshita, et al "Study of wire EDM-Imprecise measurement of mechanical behavior of electrode wire" CIRP vol. 33/1/1964, pp.84-92.

[7] V. Smolentsev, and G. Smolentsev, "Calculation of the minimum tension and speed of unprofiled electrodes" Elektronnaya Obrabotka Materialov, No 2, April, pp. 9-16, 1966.

[8] Y.F. Luo, "An Energy distribution in fast

cutting wire EDM" J. of material processing technology, 55, pp. 380-390, 1995.

[9] Y.P. Taramykin and S.G. Kulagin, "Concerning forced oscillation of an unshaped electrode." Electronnaya obrabotka materialov No 1. pp. 13-17, 1970,

[10] N. Kinoshita, et al "Study on EDM with wire electrode-gap phenomenon" CIRP vol. 25/1/1976, pp. 141-145.

[11] I.I. Sazhin, "Precision EDM capabilities with unprofiled wire electrode" Electronnaya obrabotka materialov, No. 1, pp. 79-87, 1966.

[12] A.B. Khairy, "Stochastic analysis of EEDM-turning, Proc. of 20th simulation and modeling Pittsburgh conf., pp. 264-269, 1989.

[13] S.M. Pandit, and K.P. Rajurkar, "Crater geometry and volume from electrodischarge surface profiles by data dependent systems" Journal of engineering for industry , vol. 102, Nov., pp. 289-295, 1980.

[14] H. El-Hofy, M. El-Makky and T. El-Wardany, "Surface generation in electroerosion dissolution and electrodischarge machining" Alexandria engineering journal, vol. 29, No. 4, October, pp. 301-305, 1990.

[15] K.P. Rajurkar and S.M. Pandit, "Formation and ejection of EDM debris" Journal of engineering for industry vol. 108, pp. 22-26, 1986.

[16] C. Frei, et al "A new approach for contamination measurement in EDM dielectric" CIRP 36/1/1987, pp. 111-113.

[17] W.M. Wang, et al Digital gap monitor and adaptive integral control for auto-jumping in EDM" Journal of engineering for industry, May, vol. 117, pp. 253-258, 1995.

APPENDIX

Stochastic modeling of surface profiles-

If $x_1, x_2, \ldots\ldots x_N$ are N profile measurements at a sampling interval Δ then the parameters of the discrete A(1) model is given by

$$x(t) - \Phi_1 x(t-1) = a_t \,;$$

$$\Phi_1 = \sum_{t=2}^{N} (x - \bar{x})(x_{t-1} - \bar{x}) / \sum_{t=2}^{N} (x_t - \bar{x})^2$$

The variance of uniformly sampled discrete model, σa^2, is given by

$$\sigma a^2 = \frac{1}{N-1} \sum_{t=2}^{t=N} [(x_t - \bar{x}) - \Phi_1 (x_{t-1} - \bar{x})]^2$$

$$\bar{x} = \frac{1}{N} \sum_{t=1}^{N} x_t$$

According to Pandit [13], the continuous first order stochastic model denoted by A(1), can be expressed by ;

$$\frac{dx(t)}{dt} + \alpha_0 x(t) = Z(t)$$

$$E[Z(t)\, Z(t-u)] = \sigma z^2\, \delta(u)$$

where

$x(t)$	Measured profile heights.
$Z(t)$	White noise.
α_0	Autoregressive parameter.
$Z(t)$	Has a covariance function in the form of an impulse of strength σz^2 .

Then the parameter α_0 can be given by;

$$\alpha_0 = -\frac{\mathrm{Ln}(\Phi_1)}{\Delta}$$

The profile indices can be calculated as follows ;-

Crater depth $\sigma z^2 = \sigma a^2 \dfrac{2\alpha_0}{1 - \Phi_1}$

Crater volume $Vc = 0.512\, (\sigma z^2)^3 (9/\alpha_0)^2$