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EXPERIMENTAL DETERMINATION OF THE PARAMETERS AFFECTING PRODUCTIVITY CHARACTERISTICS OF ELECTROCHEMICAL MACHINING PROCESSES

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ABSTRACT

The effect of working conditions, namely gap voltage, tool feed-rate, electrolysing current, additives to electrolyte and metal removal rate has been investigated for the electro-chemical drilling process(ECD). Tests were also performed using small additions of hydrogen peroxide (H_2O_2) as an oxygen supplier to the electrolysis bath. Some disadvantages, are discussed and merits are critically evaluated. The results are also compared with the available data in the literature. Finally, the effects of various parameters are discussed in details.

INTRODUCTION

The variables affecting the machining conditions in ECD are numerous. They differ from those of conventional cutting since machinability of metal is no longer dependent on such physical properties as shear strength, hardness,...etc. The rate of metal removal however is governed by such characteristics as atomic weight and electrochemical valency. Thus, the selection of the optimum processing parameters, for maximum removal rates, with acceptable tolerance and surface finish, is of prime importance.

Experiments were carried out to find the possible working range of the gap voltage, electrolysing current and tool feed rate. This was followed by a group of experiments to investigate addition of H_2O_2 on the ECD process.

MATERIAL AND EQUIPMENTS

1. Test Specimens

Test specimens were made of cylindrical blanks of hardened

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steel with 23mm. diameter and 40mm. height. Its chemical composition was determined using spectrum analysis technique and is shown in Table 1.

Table 1. Constitutents of metal specimens

Fe	C	Mn	Si	Cr	Ni	S	P
98.03	0.49	0.76	0.55	0.12	0.0	0.03	0.06

2. Electrolytes

The main electrolyte used in the investigations was NaCl solution in water (100 g/L). The H_2O_2 was also used as an additive to the main solution to study its effect on the performance of ECM. The concentrations of H_2O_2 added in the NaCl solution are either 1 ml/liter or 2 ml/liter.

The electrolyte was kept in a 50 liter container fitted with a water cooling coil to maintain a constant initial temperature.

3. Electrolytic Drilling Equipment

The ECD machine used in the present investigation is shown diagrammatically in Figure 1. The main parts of the machine are the drilling unit, the centrifugal pumps, the electrolyte tank, the filteration system, D.C. power supply , D.C. control system for the D.C. motor and measuring devices.

EXPERIMENTAL RESULTS

1. Effect of Gap Voltage

The effect of gap voltage was investigated to determine its optimum value taking into consideration its effects on ECD process with respect to electrolysing and tool feed rate.

i. Effect of Gap Voltage on the Critical Tool Feed Rate
(sparking limit)

Sparking takes place if a critical value of the tool feed rate is greater than the anodic dissolution of the workpiece. Thus the electrolytic frontal gap decreases continuously as machining proceeds till it attains a critical small value, at which sparking occurs causing severe damage of tool and workpiece. Another cause of failure is the lodging of non-conducting particles in the gap [1]. The particles disturb the flow forming an area where machining is retarded. Bridging of the gap and consequent arcing sometimes occur. Conducting particles can also cause bridging and failure.

The limiting values of tool feed rates (sparking limits) are shown in Fig.2. It clearly shows that, the critical feed rate increases very slightly within the voltage range 25-32V. However, it is preferable to use smaller values of gap voltages 20-25V in order to save energy and reduce the machining cost.

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ii. Effect of Gap Voltage on the Electrolysing Current.

Fig.3, shows the effect of gap voltage on the current passing
in ECD at different tool feed rates. It is shown that, at
the voltage range of 20 to 32V, any increase in the feed rate
will increase the machining current up to a certain value de-
pending on the potential across the gap.

At low voltages of 20-22V there is a general trend of an
increasing current with the gradual increase in gap voltage.
This may be due to the increased electrolyte conductivity as
caused by the elevation of electrolyte temperature due to the
higher current.

At a high gap voltage of 32V, values of the electrolysing
current are generally lower than those at 25V except for low
feed rates of 0.55 and 1 mm/min. This may be due to the high
rate of gas evolution and water evaporation, which decreases
the electrolyte conductivity. The liability to spark forma-
tion also increases due to electrolyte salt accumulation in
the gap.

iii. Effect of Gap Voltage on the Metal Removal Rate.

Fig.4, shows clearly that the relations between gap voltage
and metal removal rate are non-linear and nearly similar to
that shown in Fig.3.

At a high gap voltage of 32V, the metal removal rate is gene-
rally high, except for high values of tool feed rates, i.e.
2.15 and 2.45 mm/min. For the latter value, the decrease in
metal removal rate is so marked that the process appears to be
inferior to the case of 1.75 mm/min. This may be due to the
decrease in electrolyte flow-rate with increased feed rate.
Increasing the flow rate enhances the mechanical removal of
solid products and increases the rate of mass transfer of dis-
solved products. On the other hand, at high voltages and high
feed rates, the electrolyte flow-rate will be small and the
temperature within the gap increases to a maximum value, which
corresponds closely to the boiling point of the electrolyte.
Accordingly the accumulation of gas bubbles on the walls of
electrodes will increase the resistance to metal dissolution.

It is also observed that lower removal rates are obtained at
the low gap voltage of 20V, but increasing the voltage up to
22 V results in higher removal rates, for which the value
increases progressively with feed rate. This behaviour may be
related to the active state of the metal in the range of
20-25V. It dissolves by the removal of cations from the crys-
tal planes, and the rates of dissolution depend on the geome-
try of the plane [2].

Increasing the gap voltage to greater than 25V, forms a solid
oxide film on the anode surface and dissolution takes place in
a random manner over the metal surface. The process is there-

fore controlled by the film and not by the geometry of the crystal plane, with notable reduction in metal dissolution rate.

Evolution of non-conducting hydrogen gas bubbles at the cathode surface increases the anode-cathode gap resistance, especially at high feed rates. In this case, electrolyte flow rate decreases with subsequent lower rates of gas removal. Thus, it is the cathode effect [3] that causes the non-linearity of the relationships shown in Fig.4.

2. Effect of Electrolysing Current

The variation in the electrolysing current was investigated to determine its effects on ECD process with respect to tool feed rate and metal removal rate (current efficiencies).

i. Effect of Electrolysing Current on the Tool Feed Rate

Fig.5, shows the measured (F_{exp}) and theoretical (F_{th}) feed rates, as a function of the electrolysing current ,(I). It is shown that, as the electrolysing current increases both F_{exp} and F_{th} increase linearly.

The theoretically expected feed rates, F_{th} , as obtained from Faraday's law [2] at Z=2, A=55.85 g, F*=96500 C, a = 7.86 g/cm³ for steel anode and A* = 1.7472 Cm². is given by:

$$F_{th} = 12.53 \times 10^{-3} \quad I \text{ mm/min.} \tag{1}$$

The measured values of feed rates, F_{exp} , are used in conjunction with theoretical values, F_{th} , to obtain various values of the current efficiency η_f, which is defined as the ratio (F_{exp}/F_{th}).

Fig.6, shows that at low values of electrolysing current ranging from 90 to 225A, the current efficiency was markedly affected by gap voltage. A higher current efficiency was obtained at a lower gap voltage of 20V. Absence of gas generation on the frontal gap is more likely the reason. Thus, a small amount of electrolysing current was consumed in the side dissolution effect.

At high electrolysing current greater than 225A, the current efficiency increases very slightly with electrolysing current at gap voltages of 22 to 25V. The accumulation of gas bubbles and ferrous and ferric compounds on the frontal gap, increases the resistance to dissolution in the frontal direction and accordingly the current will be consumed in the side gap. But, at a gap voltage of 32V a sharp increase in current efficiency was observed as a result of the increase in anode potential and electrolyte temperature, which increases the conductivity.

ii. Effect of Electrolysing Current on the Metal Removal Rate

The relationships between electrolysing current and metal remo-

val rate are shown in Fig.7, at different gap voltages. Theoretical metal removal rate, m_{th} , was obtained from Faraday's law at A=55.85 g, Z=2 , F* = 96500 C, ρ_a=7.86 g/Cm³, for steel anode.

Hence, $\quad m_{th} = 17.4 \times 10^{-3}$ I g/min $\hspace{2cm}$ (2)

It is clear from Fig.7, that, at the working voltage range of 20-25V, a straight line relationship holds. But, at 32V, the relationship is non-linear. In the latter case, the metal removal rate increases up to a certain value, after which any further increase in the electrolysing current will decrease the metal removal rate. This phenomenan can also be attributed to the high rate of gases evolution and water evaporation, which decreases the electrolyte conductivity.

From the above discussion it can be concluded that a higher metal removal rate can be obtained using a gap voltage of 22V.

Plots of current efficiency for the metal removal rate, η_m, as a function of the electrolysing current are shown in Fig. 8. The plots show that, as the current increases the current efficiency slightly increases. That is possible due to the increase in extraneous anodic reactions (for example, gas evolution). The rate of these reactions increases with the electrolysing current and, therefore, reduces the current belonging to the anodic dissolution. This can be compared with the findings obtained by Mileham and other [4], during the ECM of medium and low carbon steels in NaCl aqueous solutions. His results show a reduction in current efficiency, which is associated with a change in the valency from Fe^{2+} to Fe^{3+} , as either the current density is increased or the electrolyte inlet velocity is decreased. Also Chin and Wallace [5], claimed that in a 4N NaCl electrolyte, it was the oxidation of a ferrous compound to a ferric compound at this metal/salt layer that caused the drop in current efficiency with increased current density.

3. Effect of Tool Feed Rate

The variation of the tool feed rate was investigated to determine its effect on ECD process with respect to electrolysing current and metal removal rate.

i. Effect of Tool Feed Rate on the Electrolysing Current

Fig.9, represents the relations obtained experimentally between electrolysing current and tool feed rate. These results show, the electrolysing current generally increases with the tool feed rate in a linear manner. It is obvious that higher values of the electrolysing currents are obtained at a gap voltage of 22V with different tool feed rates.

ii. Effect of Tool Feed on the Metal Removal Rate

Fig.10, shows that the metal removal rate increases in a linear

manner with the tool feed rate until a certain critical value, after which the tool damage occurs. Larsson and Baxter [6] obtained similar results and they reported that, the causes of tool damage can be related to high feed rate that leads to small gap and consequently the electrolyte flow rate would be reduced. The proportion of gas evolved may therefore be increased and the electric field strength would also be increased.

In practice, as the tool feed rate decreases the inter-electrodes gap increases and the current density decreases so that the metal removal rate gradually diminishes. For a large gap the process would come to a steady state.

Fig.10, also shows that higher values of the metal removal rate are obtained at a gap voltage of 22V with different tool feed rates.

If the frontal gap is decreased beyond a certain value, an increase in potential gradient would result in arcing and the process would come to a stop. It has also been reported [7] that, in some cases the sludge produced during the process could coat the electrodes resulting in complete halt of the anodic dissolution and short-circuiting of the inter-electrodes gap.

4. Effect of Adding H_2O_2 to the Solution

The effect of adding H_2O_2 as an oxiding agent to the electrolysing cell was investigated to study its effect on ECD process with respect to tool feed rate and metal removal rate (current efficiencies), at the optimum gap voltage of 22V.

i. Effect of Electrolysing Current on the Tool Feed Rate

From Fig.11, it can be seen that, at an electrolysing current range of 100-280A, the tool feed rate with peroxide-free NaCl solution is higher than that obtained in the presence of H_2O_2. It may be assumed that the O_2 liberated from the decomposition of H_2O_2 must have been consumed for oxidizing the ferrous products forming a protective film on the anode surface, which was not present in the peroxide-free bath. Thus, the ECM performance is closely related to the structure of the oxide film formed on the anode.

Also, at electrolysing currents higher than 280A, the tool feed rate in presence of H_2O_2 increases more pronouncly than that obtained in the case of peroxide free solutions. The reason for this behaviour is that a portion of the excess oxygen contained in H_2O_2 is liberated, acted as depolariser and combined with the hydrogen at the cathode forming water, thus reducing the polarization effects.

Fig.11, also shows that, the tool feed rate decreases with the increase in the concentration of H_2O_2 at low electrolysing currents, due to the increase in the oxidizing effect of O_2 at

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the anode. But the tool feed rate increases with H_2O_2 concentration increasing at high electrolysing currents due to depolarization effects oxygen at the cathode.

From this discussion and the results of Fig.12, it is clear that better current efficiencies for tool feed rate was obtained with H_2O_2-free NaCl solution at low electrolysing current values. But the highest values of current efficiency for tool feed rate was obtained with NaCl solution containing H_2O_2 at high electrolysing currents. Also, the current efficiency decreases with the increase in H_2O_2 concentration at low electrolysing current ranges and increases sharply with increasing H_2O_2 concentration at high ranges.

Therefore, H_2O_2 improves that current efficiency and increases the tool feed rates at only high electrolysing current values, where the cathode polarization has great values.

ii. Effect of Electrolysing Current on the Metal Removal Rate

Figs. 13 and 14, generally, show that, as the electrolysing current increases, the metal removal rate and current efficiency increase linearly up to a certain value, after which spark between the cathode and the anode is liable to occur. On adding H_2O_2 , a higher metal removal rate was obtained. This is due to the O_2 liberated from H_2O_2 decomposition, which which combines with hydrogen at the cathode forming hydroxyl ions (OH^-). These ions migrate or move toward ferrous ions Fe^{2+} forming a ferrous hydroxide at some intermediate position between the anode the cathode sites. This will be followed by the chemical oxidation of ferrous hydroxide to hydrated ferric oxide or rust by the oxygen present in the solution [8].

An important conclusion is that, since the ferric hydroxide is formed away from the surface of the metal, it will not have any effect on the rate of dissolution. The last phenomenon tends to increase the metal dissolution rate and decrease the polarization effect of hydrogen bubbles accumulating on the cathode surface.

It is observed that, through the electrolysing current range of 100 to 175A, the metal removal rate and current efficiency decrease with the increase in H_2O_2 concentration.

At electrolysing currents of 175 to 250 A, the metal removal rate and current efficiency increase to higher values with the increase in H_2O_2 decomposition.

Also, it is observed that, at electrolysing currents greater than 250A, a sudden drop in the metal removal rate and current efficiency takes place with the increase in H_2O_2 concentration. This may result from the excess amount of O_2 formed tending to oxidize ferrous compounds to ferric ($Fe_2O_2.H_2O_2$), which precipitate on the anode surface and increases the resistivity to current flow.

In general, addition of small amounts of H_2O_2 to NaCl solution will increase the metal removal rate and consequently, the current efficiency will increase. The latter can be attributed to the extra O_2 atom's effect on the polarization of hydrogen bubbles forming hydroxyl ions, which enhances the dissolution of ferrous ions from the anode surface.

5. Effect of Tool Feed Rate

The variation of the tool feed rate in the presence of H_2O_2 was investigated to determine its effect on ECD process with respect to electrolysing current and metal removal rate.

i. Effect of Tool Feed Rate on the Electrolysing Current

Normally, the electrolysing current increases by increasing tool feed rate. This holds also as a general trend as shown in Fig.15, although the rate of current increase is affected by the presence of such oxidizing materials as H_2O_2.

There are two distinct features in the current behaviour:

a- As the tool feed rate increases (up to 1.75 mm/min.), addition of H_2O_2 increases the electrolysing current and the more H_2O_2 added, the higher the current will be. Nevertheless, the rate of current increase is lower than that on using NaCl alone as an electrolyte and the higher the concentration of H_2O_2 , the lower will be the increase in current rate. Consequently, two case of similar effects for electrolysing current on the tool feed rate appear:

1. At 235A for 1.45 mm/min. tool feed rate either for NaCl electrolyte alone or with 0.2% H_2O_2.
2. At 285A for 1.85 mm/min. tool feed rate whether with NaCl alone of admixed with 0.1% H_2O_2.

The above mentioned behaviour at low feed rates may be explained by the depolarization effect of released O_2 in the electrolysing bath. This point of view is supported by the findings of Hoare and others [9] on comparing polarization curves for Fe anode in oxygen and nitrogen saturated $NaClO_2$ solution. The presence of O_2 increases the current density.

b- For feed rates exceeding 1.75 mm/min. revers tendencies are observed; the presence of H_2O_2 decreased the electrolysing current and the higher the concentration of peroxide, the lower will be the obtained electrolysing current at similar feed rates.

The rate of increase of electrolysing current with feed rates declines with the increase in the amount of peroxide present. This can be explained by the increased insolubility of ferric precipitates around the anode, that brings about a state of supersaturation within the anolyte region. Ferric precipitates may thus form a porous layer on the anode surface and hence the resistivity will increase. Thus, the addition of peroxide at high tool feed rates lowers the electrolysing current and con-

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sequently decreases the power consumption.

ii.   Effect of Tool Feed Rate on the Metal Removal Rate

The relation is linear between feed rate and metal removal rate
in the NaCl electrolysing bath showing an increase in the latter
with the former parameter. And, as presented in Fig.16, the
presence of oxygen in the bath, through H_2O_2 addition, has a
marked effect, as it causes an increase in metal removal rate.
The presence of H_2O_2 increases the hydroxyl ions concentration
in the electrolysing bath, which consequently increases the
conductivity. On the other hand, polarization effects are
reduced.

The metal removal rate increases by adding more peroxide at the
same tool feed rate. But, a decline in this behaviour appears
near a tool feed rate of 2 mm/min. Consequently the metal re-
moval rate is at that limit, which makes the peroxide presence
of no significance. Nevertheless, slight addition of 0.1%
peroxide plays its role of increasing the metal removal rate
as the feed rate exceeds the value of 2 mm/min.

Although, the rate of increase of metal removal with tool feed
rate in the electrolyte bath having 0.2% H_2O_2 was higher in
the first third of the experiment, it seems that the decrease
in electrolyte flow rate, caused by increasing the tool feed
rate, results in the accumulation of electrolyte salts on the
anode surface. Consequently, the metal removal rate declined
in the second third of the run. The marked drop in metal re-
moval rate in the last third of the curve, at higher tool feed
rates, is a result of conductivity decrease. The decrease in
electrolyte flow as a result of increased feed rates changes
the electrolyte mixture from a single liquid phase flow into
a mixed-liquid gaseous phase. The effect on conductivity is
considerable.

In addition, the drop of metal removal rates at higher concen-
trations of oxygen, when tool feed rates are high, causes an
increase in ferric precipitates rust accumulating as a protec-
tive film on the anode surface. As a result, the resistivity
is increased at high tool feed rates.

INTERPRETATION OF THE RESULTS

The outcome of the experimental study can be summarized as
follows:
It is desirable to keep productivity as high as possible and
here an important factor is to use a high feed rate. Therefore,
for an electrolytic drilling operation to be performed success-
fully (i.e. without danger of sparking) at any gap voltage,the
tool feed rate must be selected to be lower than the correspond-
ing critical feed rate at the same gap voltage. Sparking and
critical breakdown in ECD appear to be associated with the for-
mation of a gas blanket over one of the electrodes, and the
anodic dissolution of the workpiece is lower than the tool feed

rate. The critical feed rate (sparking limit) is slightly affected by increasing gap voltage.

At high feed rates of 1.75 to 2.45 mm/min. there is a general trend of decreasing the electrolysing current and metal removal rate with increase in gap voltage. Therefore, smaller values of gap voltages prove to be preferable in conjunction with energy consumption and machining cost.

Recalling the effect of variation of tool feed rate with electrolysing current for gap voltages ranging between 20 and 32V, Fig.5. All the points collect in a region between two margins. The lower side extends from 75 to 125A at 0.55 mm/min. tool feed rate (line A-A). The upper side varies from 300 to 380A at 2.5 mm/min. tool feed rate (line B-B). Values of electrolysing currents scatter in between. It is obvious that all points scattered in the region shown give tool feed rate values less than theoretical for any electrolysing current. The cause is that actual working conditions are different with respect to solubilities conductivity, phases and other variables than theory. For gap voltages considered in this work, the values of current efficiencies for tool feed rates at different electrolysing current are found to be mostly confined in a range of 45-60% Fig.6.

The same approach can be made to metal removal rate-electrolysing current relationship shown in Fig.7, the obtained value at different gap voltages are scattered in a range lower than theoretical relationship line due to variation in actual experimental conditions. This is shown in Fig.7, with the two dashed lines. Neverthless, most of the efficiency values for metal removal rate for different gap voltages are found to be within the range of 50 to 60% as shown in Fig.8.

A general trend was observed that, the current efficiency for tool feed and metal removal rates has a declining rate of increase with increase of electrolysing current, Figs 6 and 8. The mode of removal is similarly affected. In particular, the metal/electrolyte interaction is closely linked with the formation of surface films, which play a dominant role in determining both the rate and the manner of dissolution. Therefore, the key to good dimensional control as well as to the quality of surface finish in ECD is a direct function of the properties of those films.

From this discussion it is clear that, at low electrolysing current values, better current efficiencies for tool feed rate were obtained with H_2O_2-NaCl solution.

On the other hand, at electrolysing currents more than 280A, the highest values of current efficiency for tool feed rate were obtained with NaCl solution containing H_2O_2. This may be due to more hydrogen gas evolution at high values of electrolysing current, since, a portion of the excess oxygen contained in H_2O_2 is liberated, acted as a depolariser and combined with the

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hydrogen at the cathode forming hydroxyl ions, thus reducing the polarization effects. Therefore, the current efficiency for tool feed rate increases sharply on increasing H_2O_2 concentration at high ranges of electrolysing currents.

Furthermore it is observed that through the electrolysing current range of 100 to 175A, the current efficiency for metal removal rate decrease with increase in H_2O_2 concentration. This may be accounted for by the fact that as the liberated oxygen increases, the mixture changes from a liquid flow to a bubble-liquid mixed flow, which increases the resistivity of the electrolyte.

At moderate values of electrolysing currents of 175-250A, the current efficiency for metal removal increase to higher values with the increase in H_2O_2 decomposition. Accordingly, the polarization effect of gas bubbles will be decreased and the current passage increased and the conductivity will increase due to the presence of the OH^- of high mobility.

Also, a sudden drop in the current efficiency for metal removal rate, takes place with the increase in H_2O_2 concentration at electrolysing currents greater than 250A. This can be explained by the increased tool feed rate with increase H_2O_2 concentration, which leads to reduce the time and the amount of electrolysing current for the side anodic dissolution.

Generally, the electrolysing current increases by increasing tool feed rate. As the tool feed rate increases up to 1.75 mm/min. addition of H_2O_2 increases the electrolysing current and the more H_2O_2 added, the higher the current will be. This may be explained by the depolarization effect of released oxygen in the electrolysing bath. The presence of oxygen increases the current density.

For feed rates exceeding 1.75 mm/min. reverse tendencies are observed; the presence of H_2O_2 decreases the electrolysing current and the higher the concentration of peroxide, the lower will be the obtained electrolysing current at similar feed rates. This can be explained by the increased insolubility of ferric precipitates around the anode and hence the resistivity will increase.

On the other hand, the presence of O_2 in the bath through H_2O_2 addition causes an increase in metal removed. This can be attributed to increasing the hydroxyl ions concentration in the electrolysing bath, which consequently increases the conductivity. But, at high tool feed rates of 1.5-2.75 mm/min. the marked drop in metal removal rate was obtained. This may be due to the decrease in electrolyte flow as a result of increased feed rates and thus increase the concentration of the anode products and oxygen bubbles. Therefore, the resistivity is increased.

CONCLUSION

A systematic study was performed on different parameters governing the electrochemical drilling of hardened steel in NaCl electrolyte. Addition of H_2O_2 as an oxygen-releasing chemical was tried and proved to be advantageous.

During the study in the safe(non-sparking) zone, the optimum gap voltage of 22 volys was found for both the electrolysing current and metal-removal rates at different tool feed rates. The obtained current efficiencies for tool feed and metal-removal rates were 40-55% and 50-53%, respectively.

With respect to tool feed rates, a maximum current efficiency of 58% was obtained at as low as 20 volts of gap voltage. But, a maximum value of 62% current efficiency for metal removal rate was realised at a higher gap voltage of 32.

Minute additions of H_2O_2 to NaCl electrolyte bath are recommended to improve the tool feed rate, the metal removal rate and their current efficiencies through depolarization at high electrolysing current values. An efficiency increase from 55 to 75% for tool feed rate and from 53 to 64% for metal removal rate was achieved at the optimum gap voltage of 22V by presence of 0.2% H_2O_2 in the electrolytic bath.

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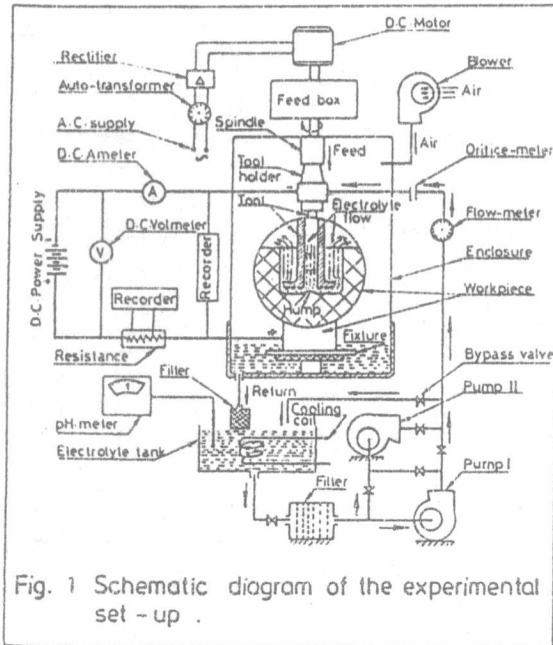   Tool Des. Res. 22,No.3, 147-158, (1982).

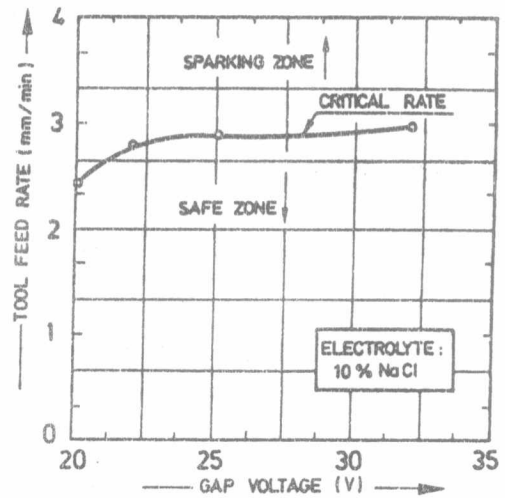Fig. 1 Schematic diagram of the experimental
set - up .

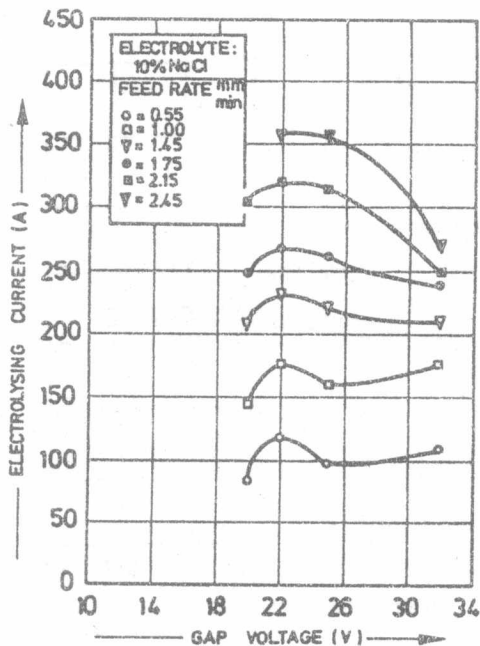Fig. 2 Effect of gap voltage on the critical
feed rate .

Fig. 3 Effect of gap voltage on the electrolysing
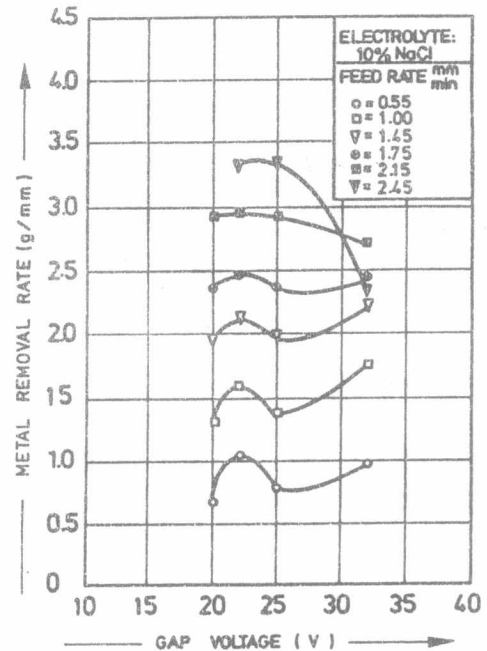current at different feed rates .

Fig. 4 Effect of gap voltage on the metal
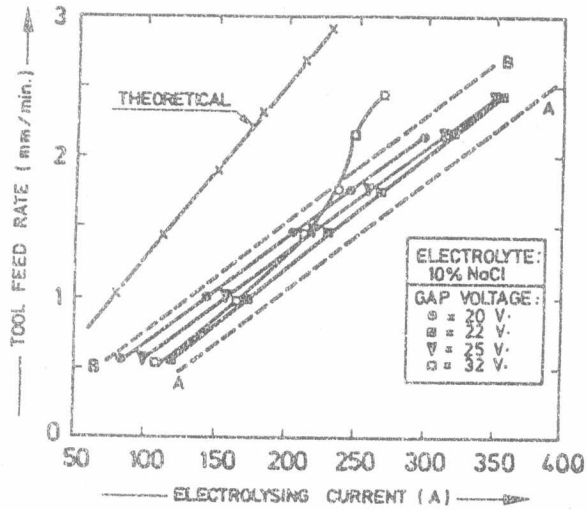removal rate at different tool feed
rates .

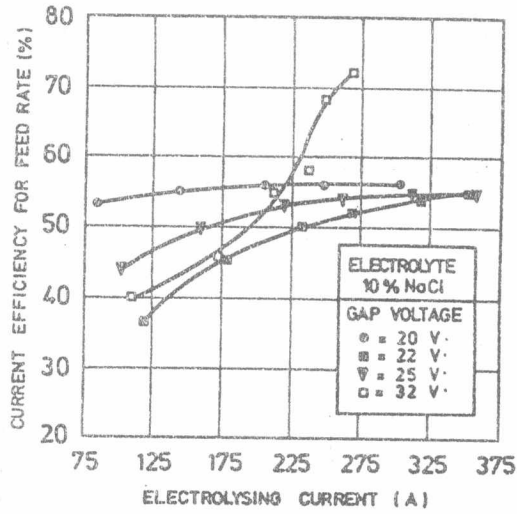Fig. 5 Effect of electrolysing current on the tool feed rate at different gap voltages.

Fig. 6 Effect of electrolysing current on current efficiency for tool feed rate at different gap voltages.
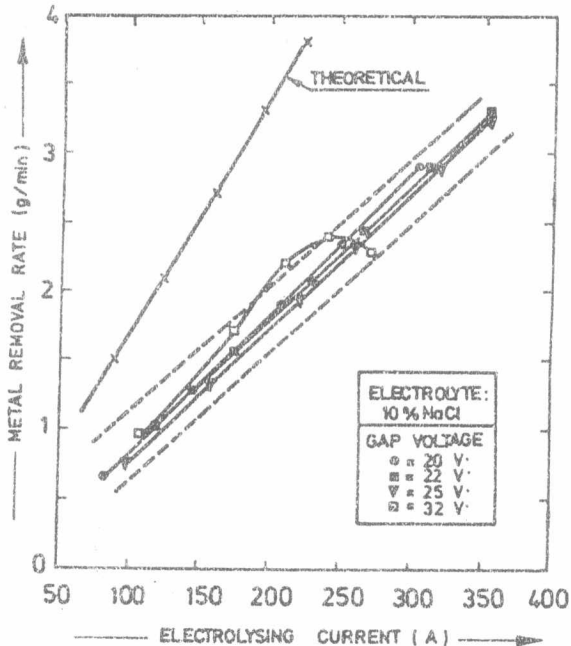
Fig. 7 Effect of electrolysing current on the metal removal rate at different gap voltages.
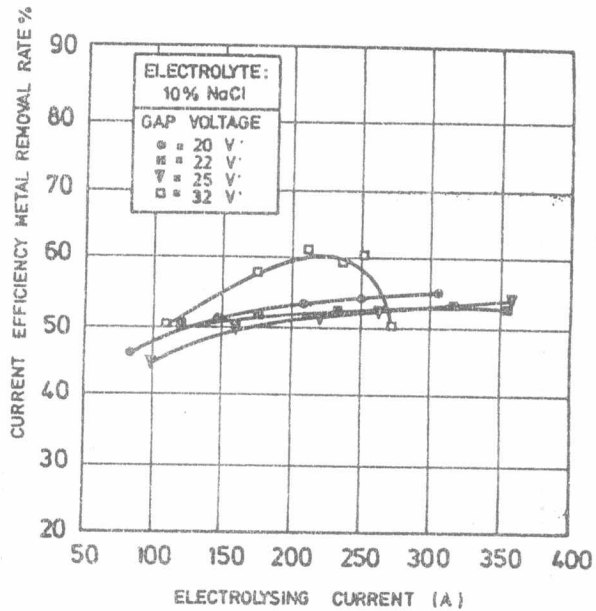
Fig. 8 Effect of electrolysing current on current efficiency for metal removal rate at different gap voltages.

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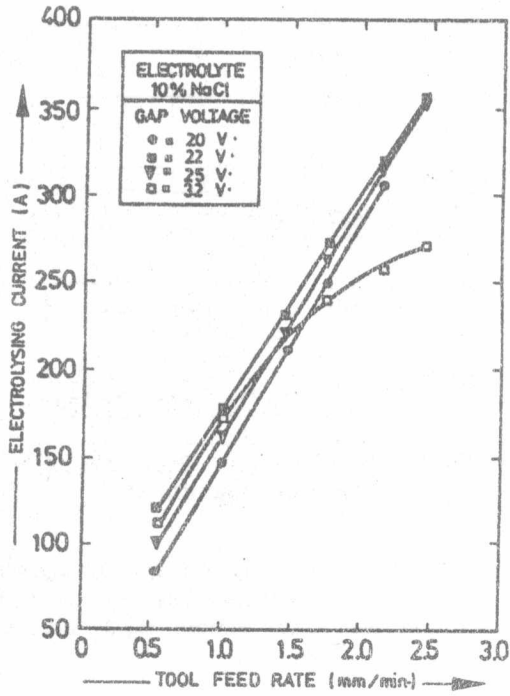
Fig. 9 Effect of tool feed rate on the electrolysing current at different gap voltages.
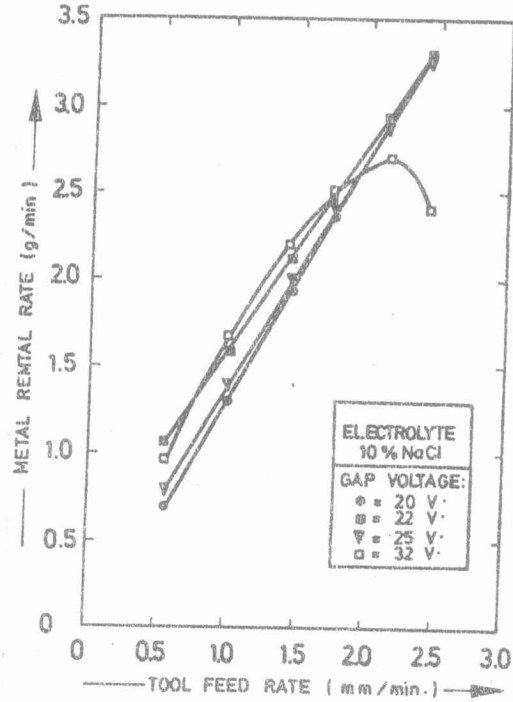
Fig. 10 Effect of tool feed rate on the metal removal rate at different gap voltages
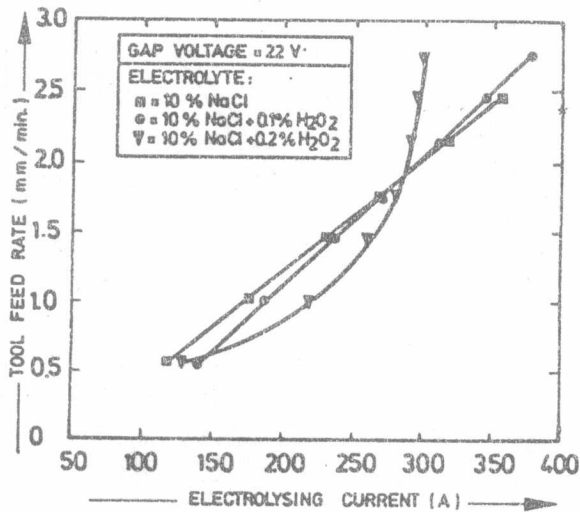
Fig. 11 Effect of electrolysing current on the tool feed rate in NaCl solution with and without H_2O_2 addition.
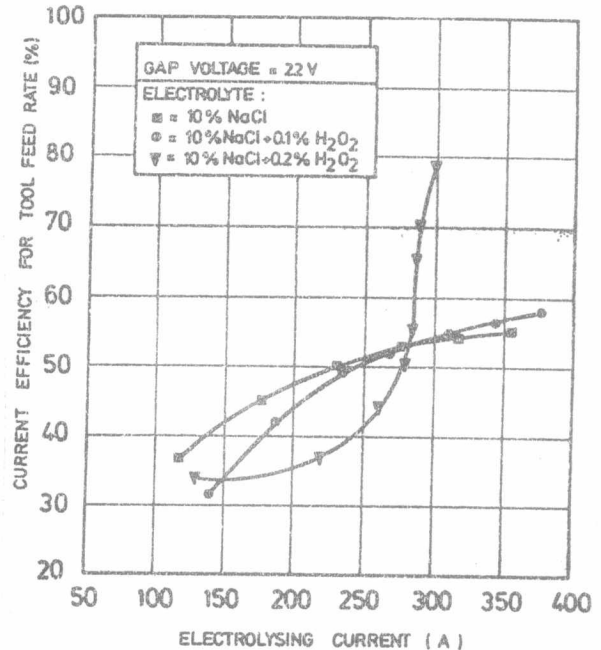
Fig. 12 Effect of electrolysing current on current efficiency for tool feed rate in NaCl solution with and without H_2O_2 addition.
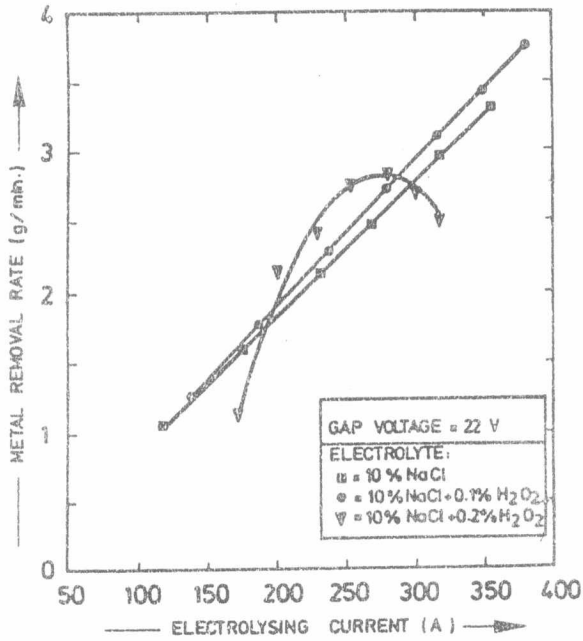
Fig. 13 Effect of electrolysing current on the metal removal rate in NaCl solution with and without H_2O_2 addition.
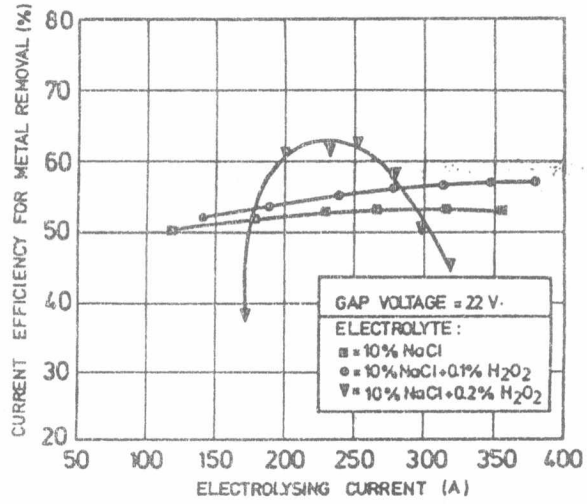

Fig. 14 Effect of electrolysing current on current efficiency for metal removal rate in NaCl solution with and without H_2O_2 addition.
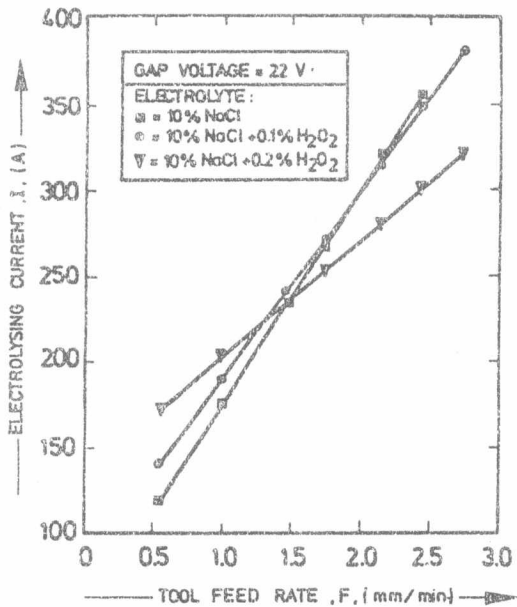

Fig. 15 Effect of tool feed rate on the electrolysing current in NaCl solution with and without H_2O_2 addition.
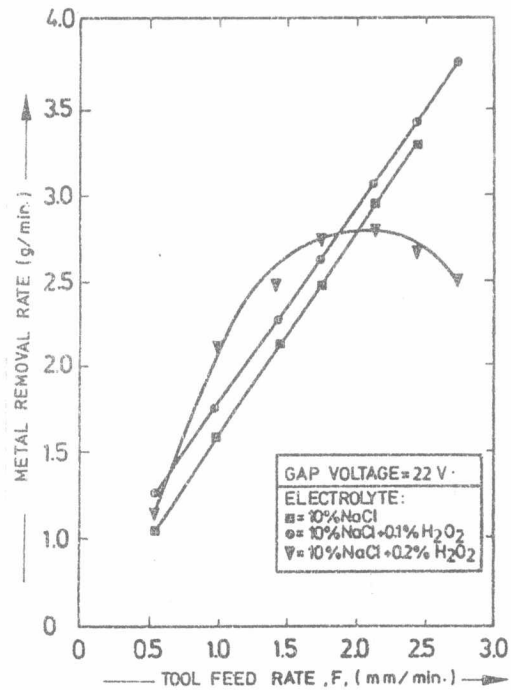

Fig. 16 Effect of tool feed rate on the metal removal rate in NaCl solution with and without H_2O_2 addition.