JOURNAL OF APPLIED ELECTROCHEMISTRY **13** (1983) 795–802

Electrochemical saw using pulsating voltage

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Received 25 February 1983

An electrochemical process for cutting metals and conducting refractory materials using a pulsating voltage has been developed. A laboratory type electrochemical saw is described which has been successfully applied to cut different metals and sintered V_2O_3. The influence of different operating variables on cutting rate and precision has been studied for the cutting of nickel in a nitrate electrolyte.

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1. Introduction

Electrochemical machining (ECM) is a metal shaping process involving anodic dissolution of the work piece at high rate under conditions of rapid electrolyte flow and small interelectrode spacing [1, 2]. ECM has a number of desirable characteristics including the independence of the machining rate on hardness, the absence of tool wear and of process induced surface stresses in the work piece and the ability to yield good surface finish. It has been shown recently that the use of pulsating instead of direct current may significantly extend the range of possible applications of electrochemical metal shaping and surface finishing operations [3–5]. In particular, by using pulsating current one can apply extremely high instantaneous current densities to the work piece without the need for an elaborate electrolyte pumping system and rigid machine frame. This is possible because each current pulse is followed by a relaxation time of zero current which allows for removal of reaction products and heat generated by the joule effect from the interelectrode gap. The average current density in pulse electrochemical machining (PECM) will, of course, usually be much lower than in direct current ECM. This limits the use of PECM to applications which do not require a high machining rate.

An interesting possible application of PECM is cutting of metals or other conducting materials. Indeed, due to the small effective surface area of the cutting tool one can use relatively small and inexpensive pulse generators and extremely simple electrolyte pumping devices. This should make the process particularly suited for small scale applications involving the cutting of hard materials such as refractory metals or for the cutting of single crystals in metallography laboratories where one wants to avoid any alteration of the crystal structure during the cutting. Indeed, among the existing methods of single crystal cutting, electrodischarge machining as well as mechanical cutting, with for example a diamond saw, lead to severe surface alteration of the cut area due to thermal effects and/or mechanical deformation. In addition, resulting surfaces are often rough and require chemical or electrochemical post-treatment. Chemical machining using acid attack is another method for cutting single crystals. However, compared to an electrochemical process the rate and precision of the chemical attack are much lower and its applicability to different metals is restricted. In the present paper an electrochemical saw developed in our laboratory [5] is described which is based on the principle of PECM. The influence of operating variables on the cutting rate and on precision is investigated for the cutting of nickel in a neutral sodium nitrate electrolyte. The applicability of the process to the cutting of other materials such as stainless steel, tungsten and vanadium oxide is demonstrated.

2. Operating principle

The electrochemical cutting process described in this paper has the following features: (i) application of a pulsating voltage at constant anode advance rate, (ii) thin blade cathode moving perpendicular to the advancing anode, (iii) electrolyte contact only in the machining gap. The operating principle is illustrated schematically in

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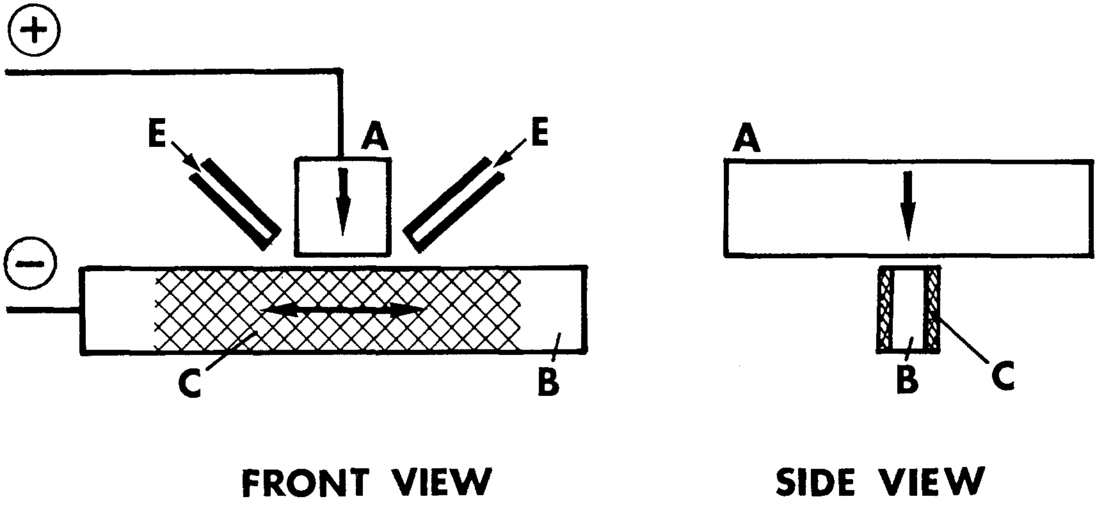

Fig. 1. Principle of electrochemical cutting operation A: work piece, B: tool blade, C: insulation, E: electrolyte.

Fig. 1. The metal piece (A) to be cut is made the anode and moves at a constant rate towards the cathode (B) which is covered by an insulation (C) on all sides except that facing the anode The electrolyte is admitted to the interelectrode gap through the capillaries (E). Supply of fresh electrolyte to the interelectrode gap and removal of reaction products and heat is accomplished by the to and fro movements of the blade forming the cathode.

3. Apparatus

The apparatus is shown in Fig. 2. It consists of four modular units: the work piece advance unit (WPAU), the tool drive unit (TDU), the electrolyte circulation system and the electrical power supply.

3.1. *Work piece advance unit (WPAU)*

The metal piece to be cut is positioned in the anode holder (Fig. 3) made out of PVC. The anode holder is fixed to the WPAU the movement of which is controlled by a variable speed motor allowing for precise control of the feed rate. The work piece is thus advanced continuously towards the tool at rates varying from 1 μm min^{-1} to 6 cm min^{-1}. There is also provision for manual movement of the work piece in both upward and downward directions. This serves for fast positioning of the work piece with respect to the blade.

3.2. *Tool drive unit (TDU)*

The tool drive unit (Fig. 4) consists of a steel frame on which are mounted a reversible variable

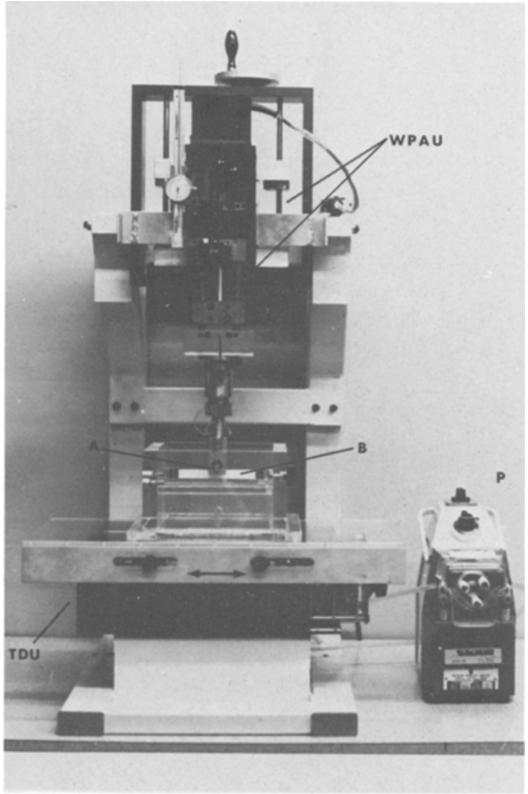

Fig. 2. Overall electrochemical saw assembly WPAU: work piece advance unit, A: work piece, B: tool, TDU: tool drive unit, P: pump.

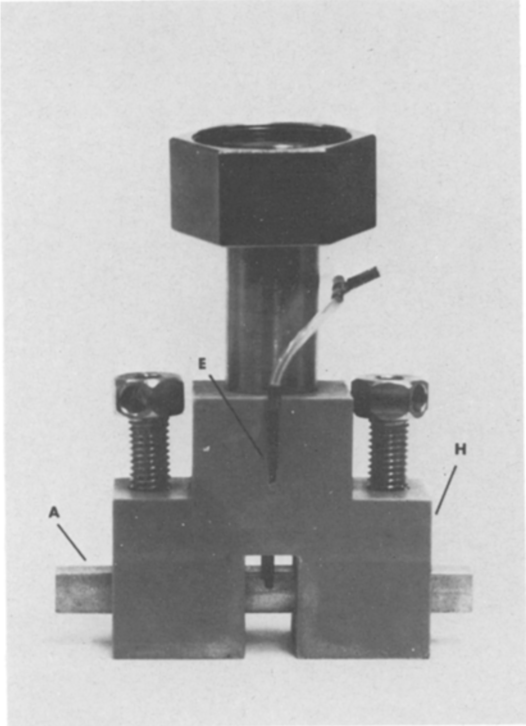

Fig. 3. The work piece holder A: work piece, H: PVC holder, E: copper tube for the passage of the electrolyte.

speed motor drive unit (MDU) and a movable plexiglas backing plate (PP). The plate is firmly supported by two metallic blocks, one of which moves over a threaded stainless steel rod attached to the motor spindle while the other carries a ball bearing assembly which moves freely on a fixed stainless steel rod. The output of the drive unit is thus transferred into linear motion of the backing plate on which is fixed a plexiglas tank T and the tool blade. Continuous to and fro movement of the tool is accomplished by incorporating two limit microswitches S_1 and S_2 into the control circuit. Whenever the tool reaches its present maximum limit the microswitches are activated which automatically reverses the direction of the motor. The stroke of the tool movement can be adjusted by adjusting the position of S_1 and S_2.

The tool blades (15 cm long x 1 cm wide x 100 μm thick) are cut from commercially available rolls of thin iron foil. The blades are degreased with acetone, etched in 10% HCl, cleaned in water and dried. The middle of these blades over a length of 10 cm on both sides is given a uniform coating of an acrylic based paint using an air spray. The painted blades are heated at 80° C for 4 h and then dried at ambient temperature for a few days before they are ready for use. One of the fronts of the blade is polished on 600 emery paper to remove the applied paint. This end serves as the cathode tool which faces the work piece. The ends of the blade left uncoated are fixed on two stainless steel holders (Fig. 4) and attached to the plexiglas tank. The tool adjust knob (K) has provisions for straightening and stretching the tool and is also used for electrical connection.

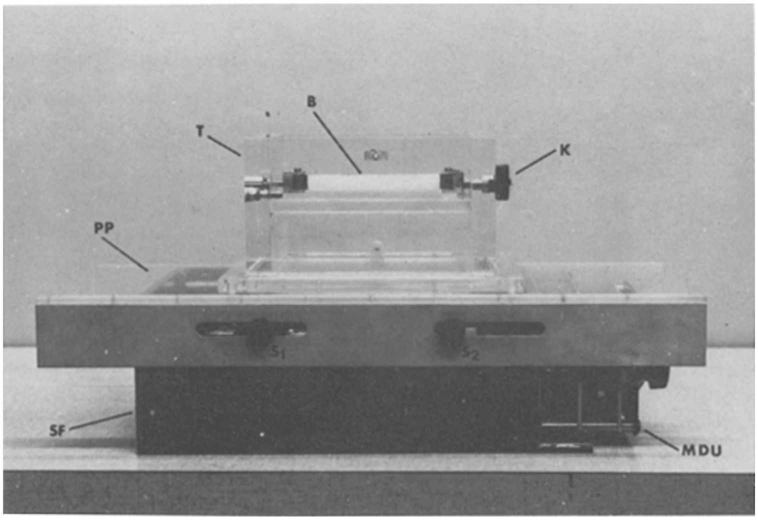

Fig. 4. The tool drive unit (TDU) SF: steel frame, MDU: motor drive unit, PP: plexiglass plate, S_1 and S_2 limit microswitches, T: tank, B: tool blade, K: tool adjust knob.

3.3. *Electrolyte circulation system*

The plexiglass tank (T) carrying the tool is used as the electrolyte reservoir. The electrolyte is circulated by means of a laboratory pump (e.g. centrifugal or peristaltic). Flexible tubing is used throughout except for two small copper tubes (E) (Fig. 3) fixed on the work piece holder and carefully aligned on the sides of the work piece such that the electrolyte falls on the blade close to the machining area.

3.4. *Power supply*

The power supply used is a pulsating voltage unit (PLSU, Egatec). The instrument can supply voltage pulses of desired amplitude (0 to 60 volts), frequency (10 Hz to 10 kHz) and duty cycle (1 to 40%).

4. Operating procedure

The initial gap between the tool blade and the work piece is fixed and the tool and the work piece are carefully aligned in parallel. The electrolyte (≈ 0.75 dm^3) is then poured into the tank. The electrolyte level must be well below the work piece in order to avoid undesired dissolution due to stray currents. Electrolyte pumping is then initiated, a typical flow rate being 6 dm^3 h^{-1}. Before starting the cutting operation it is necessary to make sure that the blade is uniformly wet. Addition of few drops of soap has been found useful to increase the wettability of the tool and work piece in order to obtain a uniform thin layer of electrolyte within the interelectrode gap. In the beginning of the cutting operation, proper surveillance is needed in order to avoid sparking problems and it may be necessary to spray a jet of electrolyte. In some cases an intermittent use of electrolyte spray may be advisable to keep the tool free from deposited reaction products and avoid sparking.

5. Experimental results and discussion

A successful utilization of the cutting machine requires proper choice of operating conditions in order to obtain a straight cut of good precision and surface finish. Indeed, localization of metal removal in the cutting region was one of the principle problems encountered during the development of the process. This has been achieved by eliminating any electrolyte contact at undesired areas of the work piece through the use of a wetted blade. However, even under these conditions cutting rate and precision may vary widely depending on operating parameters. To study the behaviour and to optimize the process cutting of rectangular nickel 200 bars (8 mm x 8 mm x 80 mm) was investigated by varying the cell voltage, feed rate, duty cycle and pulse time. 5 mol dm^{-3} $NaNO_3$ was used as the electrolyte. A measure of the cutting precision is the width of the cut compared to that of the blade. However, such a measurement was not readily obtained in the present experiments because the cut was not always uniform. This is illustrated by Fig. 5 showing a cut that is wider at the ends than at the centre. In addition, the work piece is attacked over a certain region which extends beyond the principle cutting area. To avoid ambiguity the cutting precision in the present experiments was characterized by the ratio of the volume of metal removal and the depth of cut. The smaller this ratio the better is precision.

Each cutting experiment was performed with a new blade. The total thickness of the blade including the coating was approximately 200 μm. A constant linear displacement rate of the blade of 30 cm min^{-1} and a stroke of approximately 8 cm was used. The initial interelectrode gap was 150 μm. The cutting was stopped when the anode piece had advanced a distance of 2.4 mm. Weight loss was determined by measuring the initial and final weight of the anode and the depth of cut was precisely measured under a microscope.

The optimization of different parameters was aimed at maximizing the feed rate (machining rate) and minimizing the overcut. Different experiments indicated that working at a cell voltage of 20 V or higher led to sparking which caused heavy damage to the tool and eventually the cutting experiments had to be stopped. The subsequent series of experiments were, therefore, restricted to 10 and 15 V.

Figures 6, 7 and 8 show the influence of duty cycle, feed rate and pulse time on the precision of the cut, i.e. the ratio of dissolved volume/depth. For a given feed rate and pulse time an increase in

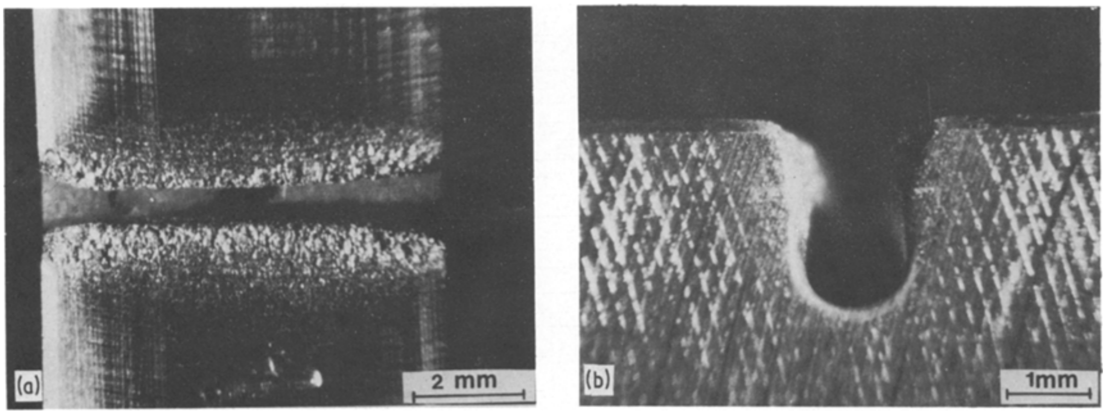

Fig. 5. Photographs showing metal removal from undesired locations giving rise to a wide cut. Metal: nickel, electrolyte: 5 mol dm^{-3} NaNO$_3$. Cell voltage: 15 V, duty cycle: 40%, pulse time: 1 ms, feed rate: 150 μm min^{-1}.

duty cycle diminishes precision (Fig. 6). For a given duty cycle better precision is obtained at higher feed rate. The maximum feed rate attainable is limited by sparking, however. Pulse time at constant duty cycle has relatively little influence within the range investigated here.

Observed results can be rationalized by considering the self-regulation mechanism inherent in voltage controlled electrochemical machining with a moving electrode under equilibrium gap conditions. In direct current ECM the overall system behaviour is governed by the ohmic potential drop in the solution so that neglecting electrode polarization one may write in a first approximation

$$I \approx V/R \tag{1}$$

where I is the current, V the applied cell voltage and R the resistance in the interelectrode gap which for plane parallel electrodes and in absence of significant thermal or gas bubble effects is proportional to the distance between the electrodes [1, 2]. In case of PECM Ohms law is applicable also and one obtains for the pulse current density i_p

$$i_p \approx \frac{V}{\kappa l} \tag{2}$$

where κ is the electrolyte resistivity (Ω cm) and l is the interelectrode distance. The pulse current density, i_p, is related to the average current density, i_{av}, by Equation 3

$$i_p = i_{av} \Big/ \frac{t_p}{t_{pp}} = i_{av}/\gamma. \tag{3}$$

Here t_p is the pulse-on time, t_{pp} the pulse period and γ the duty cycle.

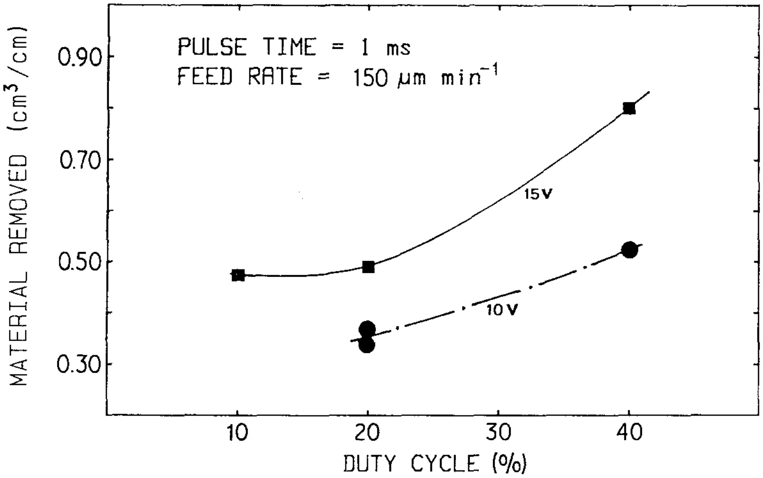

Fig. 6. Influence of duty cycle on the cutting precision of nickel in 5 mol dm^{-3} NaNO$_3$.

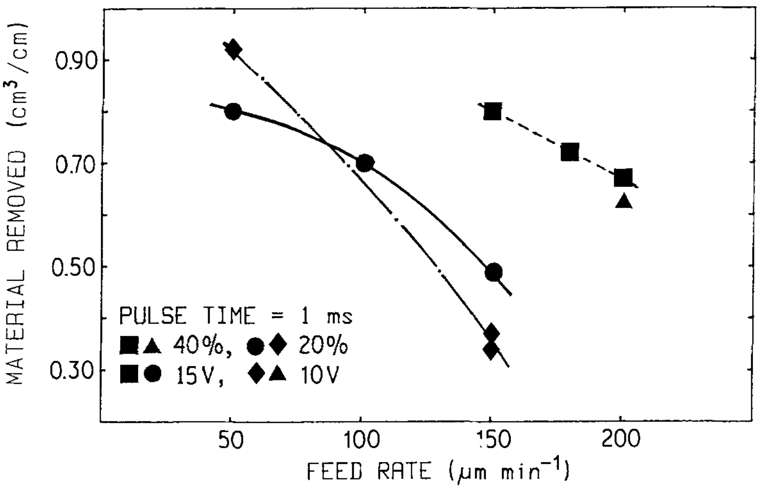

Fig. 7. Influence of feed rate on the cutting precision of nickel in 5 mol dm^{-3} NaNO$_3$.

The constant electrode advance rate f is proportional to the average current density

$$f \propto i_{av}; \quad (4)$$

It follows that the interelectrode distance l in voltage controlled PECM is proportional to the duty cycle and inversely proportional to the feed rate.

$$l \propto \frac{\gamma}{f}. \quad (5)$$

It is well known [1, 2] that in ECM the precision is usually better if one works at small interelectrode gap since this reduces the possibility of stray current attack. The results of Figs. 6 and 7 are qualitatively consistent with this fact since the amount of material removed for a given depth of the cut decreases with increasing feed rate and with decreasing duty cycle. According to the above consideration for a given duty cycle and feed rate the pulse time t_p should not influence precision. This explains the relatively small dependence on pulse time of the data of Fig. 8.

A more complete model of the cutting process would have to take into account the influence of gas bubbles, joule heating, electrode polarization and the variation of metal dissolution efficiency with current density [3, 4]. Gas bubbles and joule heating in the present application limit the maximum rate of cutting that can be achieved since they are at the origin of sparking when a critical rate is exceeded [3]. The role of electrode polarization in the case of nickel is not critical but the dependency of current efficiency on current density is an important factor [6, 7]. This can be

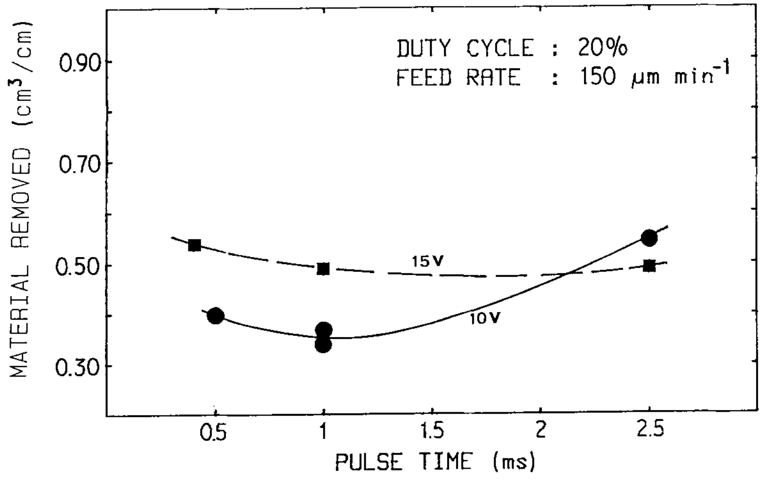

Fig. 8. Influence of pulse time on the cutting precision of nickel in 5 mol dm^{-3} NaNO$_3$.

Table 1. Cutting experiments with different materials

Material	*Electrolyte* (5 mol dm^{-3})	*Voltage* (V)	*Feed rate* (μm min^{-1})	*Pulse time* (ms)	*Duty cycle* (%)	*Remarks*
Nickel	$NaNO_3$	10–25 (10)	50–200 (150)	0.4–2.5 (1.0)	10–40 (20)	Straight cut, good surface finish were obtained using optimum conditions
Nickel	NaCl	10–15	100–150	1–2	20	Poor precision compared to nitrate electrolyte
18 to 8 stainless steel	$NaNO_3$	15	150	1	10	Relatively straight cut, good surface finish
Tungsten	NaCl	50	60	0.4	20	Poor precision, very rough surface
Tungsten	$NaNO_3$	50	60	1	10	Sparking occurred throughout the cutting operation. A straight cut was obtained but deterioration of tool resulted from sparking.
Sintered V_2O_3	$NaNO_3$	10–60 (15)	20–80 (30)	0.5–2 (1.0)	5–20 (10)	Straight cut, good surface finish, using optimum conditions. Higher feed rate required higher voltage which gave poor cut
Sintered V_2O_3	NaCl	10–30	20–100	1	5–20	Very poor cut

Figures within the ( ) indicate optimum values.

appreciated when comparing results obtained in NaCl and in $NaNO_3$ electrolytes under otherwise identical conditions. In the former electrolyte the metal dissolution efficiency is constant while in the latter it increases with increasing current density since dissolution takes place in the transpassive potential region [8]. As indicated in Table 1 much better precision is obtained with nickel in a sodium nitrate electrolyte under transpassive dissolution conditions than in sodium chloride.

The above discussion shows that proper selection of operating parameters is necessary in order to obtain an optimum cut. For nickel in nitrate electrolyte, the optimum cutting conditions are shown within parentheses in the first row of Table 1. Photographs of a cut obtained by using

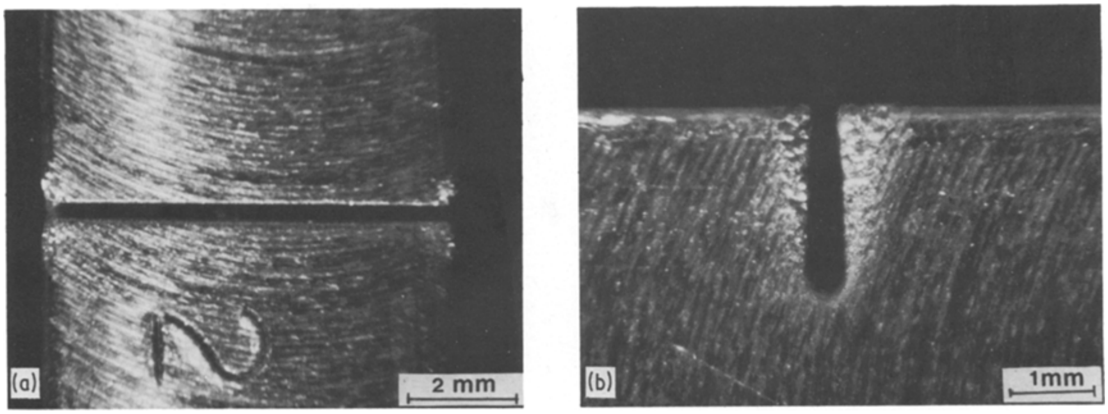

Fig. 9. Photographs showing a cut obtained under optimum operating conditions derived from different cutting experiments for nickel using 5 mol dm^{-3} $NaNO_3$. Applied voltage: 10 V, duty cycle: 20%, pulse time: 1 ms, feed rate: 150 μm min^{-1}.

these conditions are shown in Fig. 9. The cut is relatively straight with minimum stray attack.

Table 1 gives a list of different materials that have been cut and corresponding operating conditions. Under otherwise similar conditions, chloride solutions in general give poor precision resulting from stray dissolution. For cutting of tungsten 5 mol dm^{-3} $NaNO_3$ gave a better precision compared to 5 mol dm^{-3} NaCl but deterioration of the cutting tool resulted from heavy sparking occurring throughout the cutting experiment. Sodium hydroxide solution may be a better suited electrolyte for the cutting of tungsten and its alloys but has not been tested here [9]. Electrochemical cutting has also been successfully employed to cut sintered and doped V_2O_3, an electron conducting ceramic material. Different parameters were varied in order to obtain a straight cut with good surface finish. The data presented in the last two rows of Table 1 indicate that better results are obtained in nitrate electrolyte. Compared to other materials, the cutting rate for V_2O_3 under optimum conditions is relatively small (30 $\mu m\,min^{-1}$). A higher cutting rate could be achieved at higher voltage but resulted in poor precision.

6. Summary and conclusions

It has been shown that the process of PECM can be successfully applied to the cutting of conducting materials. A prototype of an electrochemical saw has been built and used to cut different metals as well as sintered V_2O_3. The unique features of the apparatus are the pulsating voltage and the wetted tool blade which permit the cutting operation to be performed without the need of high electrolyte flow velocities or strongly aggressive acid solutions. By using a simpler advance unit and a pulse generator with a properly optimized range of duty cycle, frequency and amplitude, it should be possible to further reduce the cost of the apparatus without negatively affecting its performance. The experiments presented in this study were aimed at optimizing conditions for cutting of nickel in nitrate electrolyte. For other metal–electrolyte systems optimum conditions will be different from those given here. However, the results of the present study can be taken as a guide line which should minimize the time and effort involved in obtaining optimum conditions for cutting different materials.

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