ELECTROCHEMICAL MACHINING (ECM) WITH ALTERNATING CURRENT

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Abstract

Electrochemistry has had several practical uses in industry for a long time; but one of the more recent applications is the machining of metals. Direct current ECM has been applied in industry for the last two decades. However ECM with alternating current is still in the early stages of research and development. This paper shows that ECM with normal a.c. supply is feasible and practicable if special tools are used. ECM with d.c. is first introduced to provide a better insight for the machining with a.c.

1. Introduction

1.1 ECM with d.c.

In the past twenty years or so, novel machining techniques have been spurred to existence by (a) specification of superalloys and refractory materials in the aerospace industry (b) increasing complexity and sophistication in design philosophy and (c) escalating costs of conventional machining methods. Amongst the newcomers are :—

1. Electrical Discharge Machining (EDM).
2. Ultrasonic Machining (USM).
3. Electron Beam Machining (EBM).
4. Laser Beam Machining (LBM), and more pertinent to this paper
5. Electrochemical Machining (ECM).

Nothing more will be said here on the first four methods; interested readers can find plenty of literature elsewhere.

In ECM metal is removed from the workpiece (anode) surface atom by atom by the action of electrolytic reactions brought about by the applied potential between the two electrodes. Unlike the electroplating process, no metal is deposited on the tool (cathode) in ECM because the conditions are such that a fast high pressure electrolyte sweeps away the ions from the gap between the electrodes before plating out occurs.

ECM made its debut in industry in the early nineteen-fifties in the form of electrolytically assisted grinding; which is similar to conventional grinding except that the abrasive wheel is replaced by an electrically conductive one impregnated with a small proportion of fine abrasive. Electrolytic grinders are now commonplace in tool rooms for grinding of tungsten carbide, or similar alloy, tools. However, pure ECM was introduced in industry ten years later; but as yet it has only been fully accepted for production in the aircraft industry because they deal with much more complex designs and tougher materials.

The main advantages of ECM are :—

1. Low unit cost of manufacture, especially at hardness values more than 480HV, due to high metal removal rates.
2. Machining is independent of the workpiece hardness.
3. Tool wear is negligible.
4. There are no residual stresses, burrs or thermal damage on the workpiece.
5. Noncircular holes and other unusual shapes are easily generated.
6. Thin workpieces can be machined without distortion.
7. Machining requires only a simple, often linear, tool motion to generate complex contours.
8. Production machine tools are easy to operate.
9. Good surface finishes, 0.10 to 0.75 μm CLA, are easy to achieve.

The process has the following limitations :-

1. The capital cost of production machine tools is quite high.
2. For precise production of complex contours a considerable amount of tool development is involved.
3. Accurate results are difficult to predict, e.g. metal removal based on Faraday's laws are not achieved in practice.
4. With components where fatigue strength is critical, a post — ECM operation like shot or vapour blasting is necessary.

1.2 ECM with a.c.

The application of a.c. in ECM was suggested in the early nineteen-sixties. But so far it has not yet found its way into any industry because very little research has been done on this field.

The process has the following merits over the d.c. one:—

1. The expensive rectifying equipment associated with d.c. machining is unnecessary; only a simple high current transformer being required.

2. Polarity reversal depolarizes the electrodes, making the machining process more efficient.

ECM with a.c. is possible using two types of tool material:—

(a) Electrically conductive but electrolytically inert, e.g. graphite. This has already been successfully done (Johnson and Brown

1970, Shine 1971). Although graphite is inert, the tool wears due to mechanical action of the fast high pressure electrolyte. But with special graphite, e.g. high density graphite treated with oil, the wear can be negligibly small.

(b) Self-rectifying tools : it has been shown that titanium diboride, tantalum (Johnson and Brown 1970), titanium and aluminium (Shine 1971) form an oxide layer on the tool and that this layer depending on the frequency of the applied voltage, rectifies the current across the cell. Thus machining of the workpiece proceeds during the positive half-cycle and nothing happens during the next half-cycle.

2. Theory

2.1 Notation :

m	= metal removed (gm); $\dot{m}$ = metal removal rate (gms^{-1}); t = time(s)
z	= electrochemical equivalent (gm/coulomb); I = current (amps)
Va	= d.c. applied voltage (volts); E = reversible cell potential (volts)
ηa	= anode overpotential (volts); η_c = cathode overpotential (volts)
Vm/c	= Machining voltage (volts); Vrms = a.c. supply voltage (volts)
Vmax	= a.c. max. voltage (volts); Vm = a.c. mean voltage (volts)
ΔV	= that part of the applied voltage not contributing to current flow
Re	= resistance of electrolyte across gap (ohms); f = frequency of a.c. (Hz)
k	= conductivity of electrolyte (ohm^{-1} cm^{-1}); h = gap between electrodes (cm)
v	= tool velocity or feed rate (cms^{-1}); he = equilibrium gap (cm)
a	= cross sectional area of gap (cm^2); $h_{o'}$ = initial gap (cm)
ρ	= density of workpiece ($gm\ cm^{-3}$)
C	= $\dfrac{z\ Vm/c\ k}{\rho}$ = machining constant ($cm^2\ s^{-1}$)

2.2 ECM with d.c.

In ECM workpiece (anode), tool (cathode) and the electrolyte flowing between them form an electrolytic cell. Therefore by Faraday's laws

$$\left.\begin{array}{l} m = ZIt \\ \dot{m} = ZI \end{array}\right\} \qquad (1)$$

because the cell has a reversible potential and the electrodes develop overpotentials then

$$Vm/c = Va \pm E - (\eta_a + \eta_c) \quad \text{(2a)}$$

or $$Vm/c = Va \mp \Delta V \quad \text{(2b)}$$

and $$I = \frac{Vm/c}{R_e} \quad \text{(3)}$$

Now consider two plane-parallel electrodes normal to the feed direction as shown below

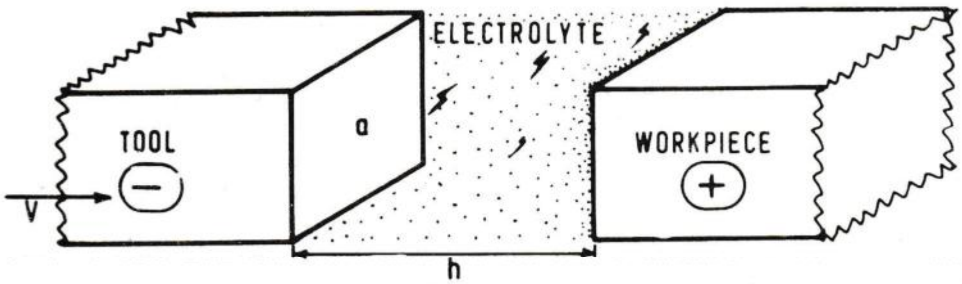


Fig. 1

$$R_e = h/ka$$

$$\therefore \quad I = Vm/c \frac{ka}{h} \quad \text{(4)}$$

and $$\dot{m} = Z\, Vm/c \frac{ka}{h} \quad \text{(5)}$$

Therefore the linear machining rate is $\dfrac{Z \quad Vm/c\ k}{\rho h}$ and if this equals the

tool velocity, then the gap is constant and $h = h_e$ giving $h_e = C/_V$ ..... (6)

If both electrodes are stationery $dh/dt = C/_h$ giving

$$h = (h_o^2 + 2Ct)^{\frac{1}{2}} \quad \text{(7)}$$

The above equations show that the gap h always tends to h_e regardless of its initial value h_o. This makes ECM self-regulating to equilibrium conditions. Also they show that for an irregularly shaped tool, the current density varies across the gap and this generates the tool face profile on the workpiece when overall equilibrium is reached as indicated below.

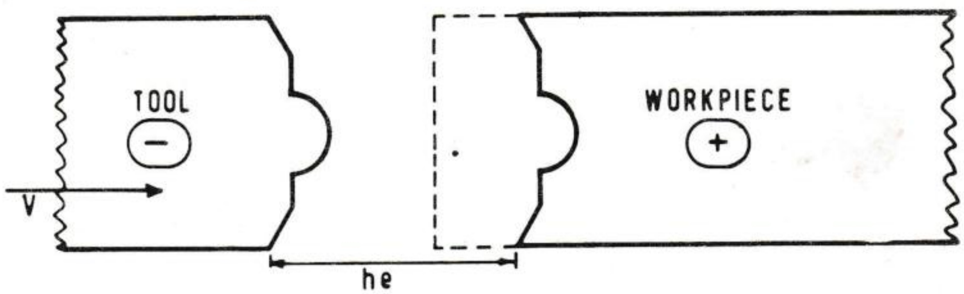


Fig. 2

2.3 ECM with a.c.

In machining with a.c. using rectifying or inert tools, only half the cycle of the applied voltage is used. The mean voltage is as shown below

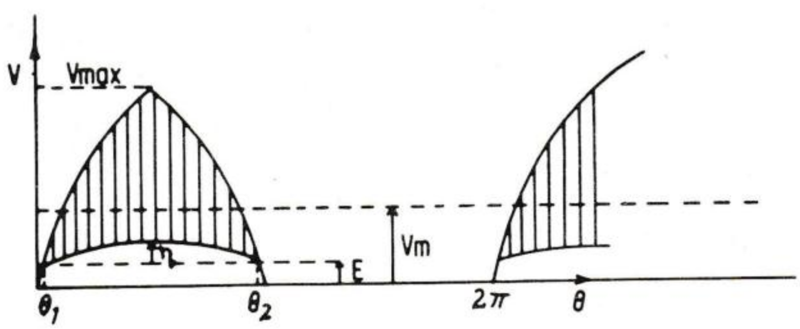


Fig. 3

θ_1 is small

$$\therefore \quad V_m = \frac{1}{2\pi}\int_0^{\pi} \left\{ V_{max}\sin\theta - E - (\eta_a + \eta_c)\sin\theta \right\} d\theta \quad \ldots.(8a)$$

taking $E = 2V;\ \eta_a = \eta_c = 0.75V$ then $V_m = \frac{\sqrt{2}}{\pi} V_{rms} - 1.5$ ..(8b)

The linear machining rate is

$$\frac{Z\ k}{\rho h} \sum_{i=0}^{i} \int_{n\pi}^{(n+1)\pi} \left\{ V_{max} \sin\theta - E - (\eta_a + \eta_c)\sin\theta \right\} d\theta$$

where $n = o, 2, 4, 6$ ....and $i = \frac{n}{2}$

It has been shown (Johnson and Brown 1970, and Shine 1971) that for $f = 50$ or 60 Hz equilibrium is reached as registered by a stable mean current and $h = h_e$

$$\therefore\ h_e = \frac{Zk}{\rho v} \sum_{i=0}^{i} \int_{n\pi}^{(n+1)\pi} \left\{ V_{max} \sin\theta - E - (\eta_a + \eta_c)\sin\theta \right\} d\theta \qquad \text{............} (9a)$$

or $h_e = \dfrac{zk\ V_m}{\rho v}$ ....(9b) Where Vm is calculated from equation (8)

It should be noted that if the frequency is very low, e.g. periodically reversing d.c., the process does not reach equilibrium with constant feed rate and equation (9) does not hold.

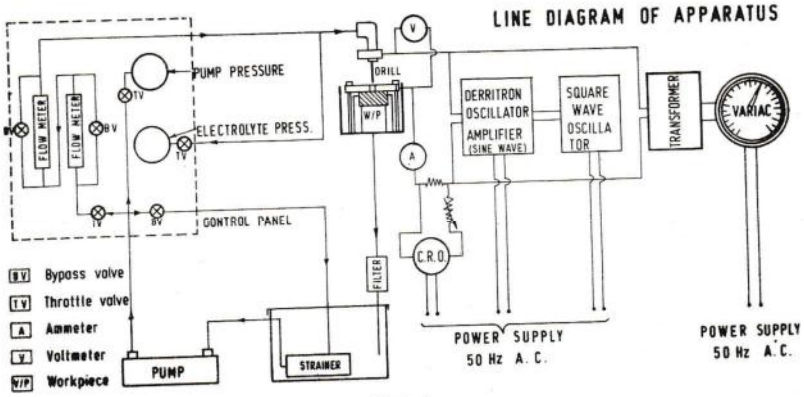
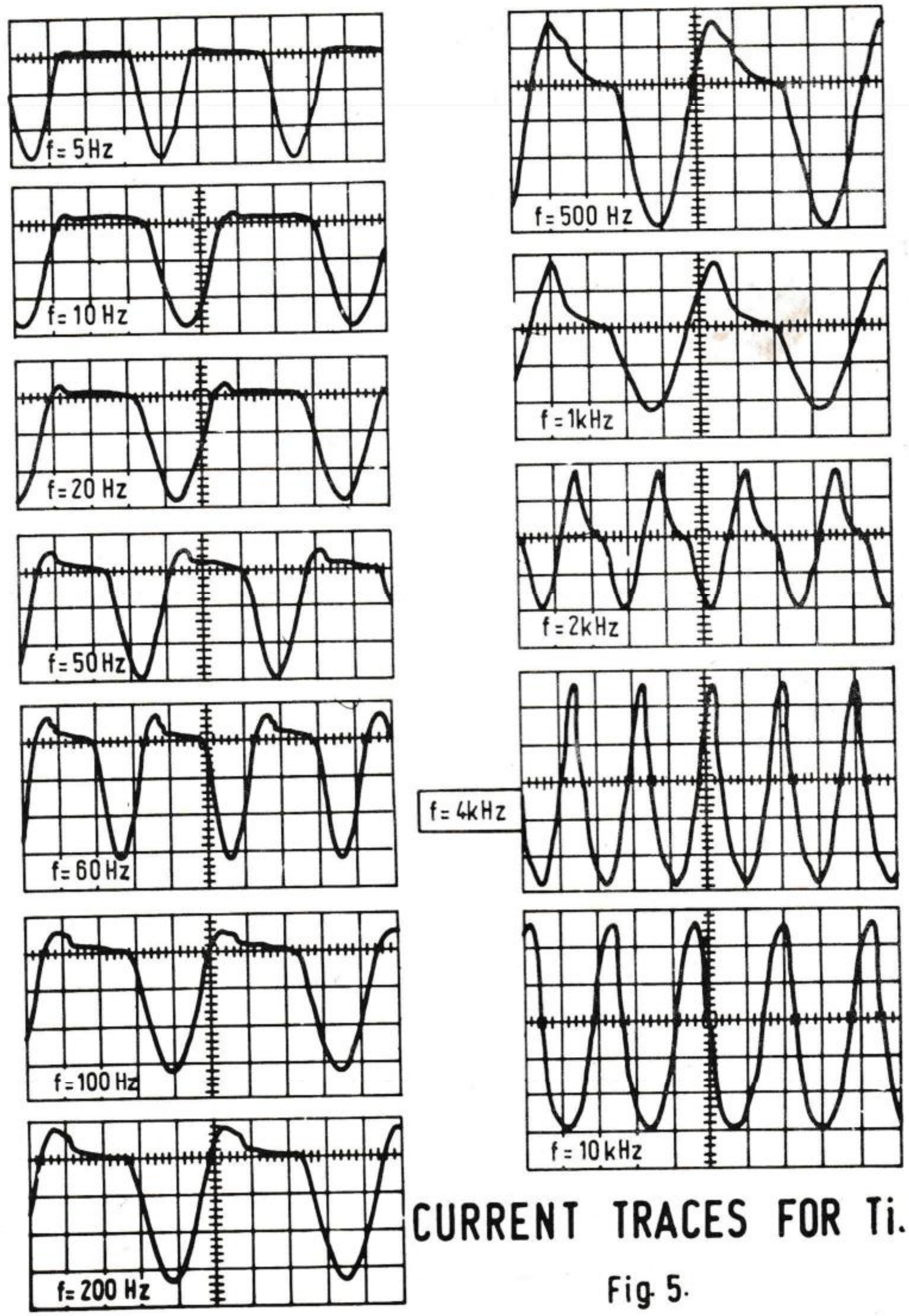


Figure 4.



CURRENT TRACES FOR Ti.

Fig. 5.

3. Discussion of Experimental Results

Figure (4) shows a line diagram of the equipment used (Shine 1971) in a.c. drilling of nimonic 100 with 10% aqueous solution of sodium nitrate as the electrolyte. Drills were made from the following materials:—

(a) 1.35mm outside diameter titanium tube coated with 0.075mm insulation (Terebec CH33).

(b) 3.0mm outside diameter aluminium tube insulated on the sides as above.

(c) 6.7mm outside diameter graphite tube.

Figure (5) shows the actual current traces photographed from the CRO Screen for the titanium drill. Similar traces were obtained with the aluminium drill. It is clear from the traces that rectification depends on the frequency of the applied voltage. For titanium almost half-wave rectification occurs at $f < 200$ Hz and at $f > 2$kHz the rectification effect disappears altogether. For aluminium almost half-wave rectification occurs at $f < 600$Hz, the effect disappearing at $f > 5$kHz.

This observation is interesting and surprising in that it makes the cause of the rectifying effect rather obscure. It was originally thought that the rectification was caused by the oxide layer which forms on the tool, similar to what happens in metal rectifiers. However, since rectification depends on the frequency this explanation may not now be entirely right. The other possibility is that the rectification which occurs across an ECM cell can be effected at the tool/electrolyte junction by asymmetrical current — electrode overpotential characteristics; an effect generally referred to as Faraday rectification (Bockris and Reddy 1970).

The exact cause of rectification occurring with these tools is not yet fully understood. However, it is of great importance to know the practical result that with the normal supply voltage of 50 or 60Hz half-wave rectification occurs with titanium, aluminium (Shine 1971), titanium diboride, and tantalum (Johnson and Brown 1970); for voltages below an optimum value. This value was found experimentally to be about 35V rms; for voltages greater than this, the oxide layer breaks down resulting in the machining of the tool as well, due to the reverse current.

Using the titanium drill, and with 50Hz normal supply voltage, stable feed rates of up to 1.78mm/min were achieved in drilling through 12.5mm specimens of nimonic 100. With d.c. drilling of the same material by the same size stainless steel drill stable feed rates of up to 6.35mm/min are possible (Jones 1969, Trethewy 1965). The slower tool feed rates with a.c. are expected because of the smaller effective machining voltage as explained in the theory. It is worth remembering here that drilling nimonic 100, or similar tough alloys, with conventional twist drills would be impossible; the other alternative would be using the other special machining techniques mentioned in the introduction.

Although drilling with graphite was done, it is not a practical proposition because of the great difficulty of making small tubes from graphite which is very brittle. But with other machining operations like cavity sinking, turning etc. graphite can be used with advantages.

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