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Experimental Investigation on MRR of Pulse Electrochemical machining (PECM) based on Taguchi Method

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Abstract: The Electrochemical Machining (ECM) is widely used in machining variety of components used in aerospace, automotive, defense & medical applications. Due to low machining accuracy ECM is yet to be a best alternative process. This paper presents experimental investigation of PECM parameters such as voltage, feed rate, and pulse on time, duty cycle on MRR. Keeping pressure constant, Taguchi's orthogonal array L_9 has been effectively used to study the effect of independent process parameters. The results show PECM has enhanced MRR. The experimental results were analyzed using analysis of variance (ANOVA) method and by plotting various graphs.

Keywords: ECM, PECM, Taguchi Method ANOVA,

I. INTRODUCTION

ECM process is generally used for machining complex shape and hard materials, ECM generates no burrs, no internal stress, has a long tool life, higher material removal rate and surface quality. Electrochemical machining (ECM) is a non-traditional process used mainly to cut hard or difficult to cut metals, and it is an anodic dissolution process based on the phenomenon of electrolysis, whose laws were established by Michael Faraday, where the application of a more traditional process is not convenient. ECM uses Electrical energy in combination with chemical reactions to remove material [1]. In traditional processes, the heat generated during the cut is dissipated to the tool, chip, workpiece and environment, affecting the surface integrity of the work-piece, mainly for those hard materials. Different from the other machining processes, in ECM there is no contact between tool and work-piece. Electrochemical (electrolyses) reactions are responsible for the chip removal mechanism [1].

In ECM, machining is done at low voltages compared to other processes with high metal removal rate; small dimensions can be controlled; hard conductive materials can be machined into complicated profiles; workpiece structure suffer no thermal damages; suitable for mass production work and low labor requirements[3,7].Predicting a minimum machining allowance or depth is essential for reducing waste generation. The uses of shorter pulse result in achieving a higher degree of localized dissolution. [3]. The stray removal in ECM adversely affects dimensional accuracy and surface quality of machined components [4].The current density and efficiency models for small gaps include the effects of polariastion voltage and the influence of electrolyte concentration and conductivity. The localisation effect at low electrolyte concentrations is utilised to achieve better dimensional control [11].

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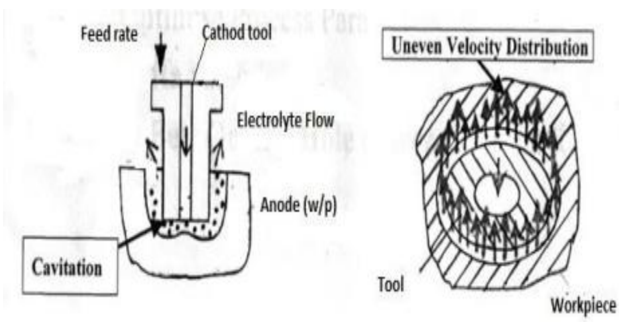
PULSE ELECTROCHEMICAL MACHINING

Principle of ECM

Electrochemical machining was developed based on the principle of Faradays law. The metal is removed by the controlled dissolution of the anode. The electrodes are connected to DC power supply ($\approx$20 V) (Fig 1), flow of current in the electrolyte is established due to positively charged ion being attracted towards cathode and vice-versa. Due to electrolysis process at cathode hydroxyl ions are released which combine with the metal ions of anode to form insoluble metal hydroxide. Thus the metal is removed in the form of sludge and precipitated in electrolytic cell. This process continues till the tool has produced its shape in the work piece.

ECM process is generally used for machining complex shape and hard materials. ECM generates no burrs, no internal

stress, has a long tool life, higher material removal rate and surface quality. However, due to its relatively low machining accuracy and electrolyte disposal, ECM is not a commonly employed in production. Hydrogen gas bubbles and Joule heating in the inter-electrode gap (IEG) causes varying local electrolyte conductivity and hence non-uniform distribution of the gap [9].The stray removal in ECM adversely effects dimensional accuracy and surface quality [6,8]. Some flow field disrupting phenomena such as cavitations and striation in electrolyte flow worsen accuracy and the uniformity of the ECM'd components. To circumvent the above problems in ECM and to improve the accuracy and quality of the machined components pulse electrochemical machining (PECM) was developed as shown in fig. 2.



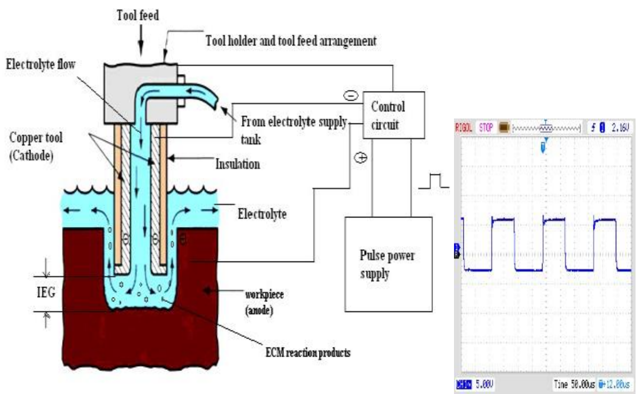


Fig1. Principle of Electrochemical Machining [4] **Fig 2. Schematic diagram of PECM Set-up**

Practice and investigations show that introducing PECM leads to:

- A reduction in inter-electrode gap to below 0.1 mm thus increasing ECM accuracy [3],
- A reduction in dimensional inaccuracies caused by internal disturbance of physical and chemical properties of electrolyte

(more exact: medium in the gap) in interelectrod gap [5]

- A simpler tool design due to the more uniform distribution of the gap size,
- A reduction in macro-defects on the machined surface connected with the hydrodynamic flow disturbances.

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Experimental set-up:

The experimental set-up used for small hole drilling (2-3mm diameter) is as shown in the fig.2.It consists of 1) tool feed arrangement (stationary tool), 2) Machining chamber, 3) Electrolyte flow system and 4) Pulse power supply. Experiment where conducted using mixed electrolyte NaNo3 (170 gm/lit) 10% by Wt HNO3 to avoid wild corrosion and sludge formation during the process .Current sensing comparator was incorporated into the tool feed arrangement to avoid short circuiting between tool and work piece, stepper motor controls the tool feed arrangement along z axis. Servo motor rotates about z axis. Machining chamber consist of table, work holding device, blow off system. Electrolyte flow system used anticorrosive submersible pump, electrolyte filter, electrolyte tank, pressure gauge and constant discharge flow control valve. Pulse power supply with constant voltage (CV) made of rectangular pulsed shape was chosen. PECM provides smaller IEG without boiling of electrolyte in gap[3], That necessitate limiting the valve of IEG across tool and work piece. Pilot experiments with smaller IEG (0.1mm) suffered due to short circuiting between work piece and tool, because of cavitation and sludge formation. The limiting current, to avoid short circuiting, was compute for controllable IEG, electrolyte conductivity and are of tool, and of operating voltage. [5] Using stationary tool feed arrangement. The sufficient electrolyte (Q=12lit/min) was maintained.
The goal of this research was to perform the experiments on ECM with coupled pulse for machining of INCONEL Super Alloy (77Ni--13Cr- 10Fe) commonly used in making turbine blades [2]
In ECM, material removal rate is independent of material hardness and for most common metals is approximately 0.10 cubic inches per minute per amperes (Machinability Data Center, 2001)[5].It shows that the MRR was influenced by various parameters (voltage, pulse on time, tool feed rate and duty cycle, electrolyte concentration, feed rate, electrolyte pressure, current density).

Experimental Design

A continuous D.C. voltage (6-18 volts) is usually applied with the current density ranging from an order of 6 A/cm^2 to 20 A/cm2. Electrolyte (typically combination of NaN03 and HNO_3 aqueous solutions) is supplied to flow through the gap with a high velocity of 10-60 m/s during PECM. The anodic electrochemical dissolution occurs during the short pulse on-times, each ranging from 0.1 ms to 5 ms.

Selecting Factors and Factor Levels

Step 1: Identifying possible factors and ranges
The preliminary design of experiments is the feasibility study and conducted to reduce the number of parameters for next randomized experiment by analyzing their statistical significance on current efficiency. Four variables are chosen in the screening design experiment including duty cycle, pulse on-time, voltage and feed rate, etc. keeping constant pressure
(1.5kg/cm^2)

Table 1. Levels and actual values of parameters in PECM

			Levels		
Sr no.	Factor	Abrivation	-1	0	1
1	Voltage(v)	A	6	12	18
2	Tool feed rate(f)	B	0.8	1.0	1.2
3	Pulse on time(t_{on})	C	50	500	1000
4	Duty cycle(γ)	D	0.48	0.64	0.80

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Step 2: Selecting factors

For this research, a 2mm and 3mm tool tip diameter electrode size was arbitrarily chosen. Since the projected area is determined by the size of electrode, current density depended merely on the voltage and feed rate, pulse on time, duty cycle. However, the power supply that was used in the experiment had a capability to adjust voltage and current by changing internal resistance. For these experiments, the current was set at a constant 5A. The response variables for this investigation have been selected as material removal rate (MRR)

Mathematically,

MRR = $(W_1-W_2)/t$----------------- (3)

Where,

'W_1' is initial height of workpiece in gm (before machining) 'W_1' is final height of workpiece in gm (after machining)

Mathematically,

MRR = $(W_1-W_2)/t.\rho$----------------

(4) Where,

ρ = density of work material in gm/mm^3

III. EXPERIMENTAL RESULTS AND ANALYSIS

S/N Ratio Analysis:

The experimental data was used to compute the S/N ratio and analysis of the parametric influence on the responses. Based on the S/N ratio optimal machining parameter was selected for a response under investigation and then verified.

Determination of S/N Ratio:

According to Taguchi method [10], the S/N ratio is the ratio of signal-to-noise where signals represent the desirable value (i.e. the mean for the output characteristic) and noise represents the undesirable value (i.e. the square deviation for the output characteristic). Therefore, the S/N ratio is the ratio of mean square deviation. Its unit is dB. The S/N ratio for each experimental run is calculated and. The obtained S/N ratio results are shown in Table 4.After conducting the DOE as per Taguchi method using L_9 orthogonal array for two repetitions following results / responses are obtained for PECM.

Orthogonal array experiment:- In the said analysis 04 (four) factors at 03 (three) levels (i.e. 9 experiments), were taken. It is found that the L_9 orthogonal array is the best suitable option.

Table 2. L_9 Orthogonal Array

Test No.	A	B	C	D
E1	1	1	1	1
E2	1	2	2	2
E3	1	3	3	3
E4	2	1	2	3
E5	2	2	3	1
E6	2	3	1	2
E7	3	1	3	2

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E8	3	2	1	3
E9	3	3	2	1

After conducting the DOE as per Taguchi method using L_9 orthogonal array for two repetitions following results / responses are obtained PECM

Table 3 Response table (for PECM)

Test	RESPONSE (Repetition)	
	1st	2nd
E1	0.007	0.009
E2	0.035	0.032
E3	0.015	0.013
E4	0.025	0.028
E5	0.041	0.045
E6	0.021	0.024
E7	0.023	0.021
E8	0.026	0.032
E9	0.043	0.04

Mean change in Voltage

ΣA_1=0.016+0.067+0.028= 0.111

ΣA_2=0.053+0.086+0.045=0.184

ΣA_3=0.044+0.058+0.083=0.185

Dividing ΣA_1, ΣA_2 and ΣA_3 by 3×2 (i.e. three factor combinations and two repetitions), the mean change in MRR under the conditions A_1, A_2 and A_3 was obtained. Thus;

A_1= 0.111/6 = 0.0185 , A_2= 0.184/6 = 0.0307 , A_3= 0.185/6 = 0.0308

Similarly calculating the mean change in tool feed rate under the conditions B_1, B_2, B_3, C_1, C_2, C_3, D_1, D_2, D_3

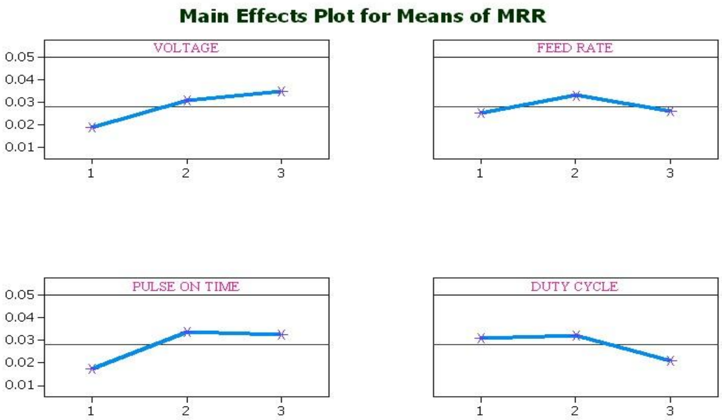

Fig. 4. Main effects plot for means of MRR in PECM

Signal to Noise (S/N) Ratio

Larger is Better (S/N) Ratio is used when there is no predetermined value for the target (T=∞), and larger the value of the characteristic, the better the voltage.

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$$\therefore\ {}^{S}/_{N}\ Ratio\ for\ A_1 = \left(\frac{(-42.14)+(-29.52)+(-37.14)}{3}\right) = -36.27$$

Similarly S/N Ratio for T_2 to T_9 was calculated and presented in table 4.

Table 4 Mean Change and S/N Ratio for Individual Factors

Factor	Total Result	Mean Change	S/N Ratio
A1	0.111	0.0185	-36.2705
A2	0.184	0.0307	-30.6500
A3	0.185	0.0308	-30.5754
B1	0.113	0.0188	-35.6325
B2	0.211	0.0352	-29.2586
B3	0.156	0.0260	-32.6048
C1	0.119	0.0198	-35.3494
C2	0.203	0.0338	-29.5860
C3	0.158	0.0263	-32.5604
D1	0.185	0.0308	-32.3857
D2	0.156	0.0260	-31.9060
D3	0.139	0.0232	-33.2042

From the calculated results of Mean change and S/N ratio Mean effects of individual factor such as A_1, A_2 etc. are plotted.

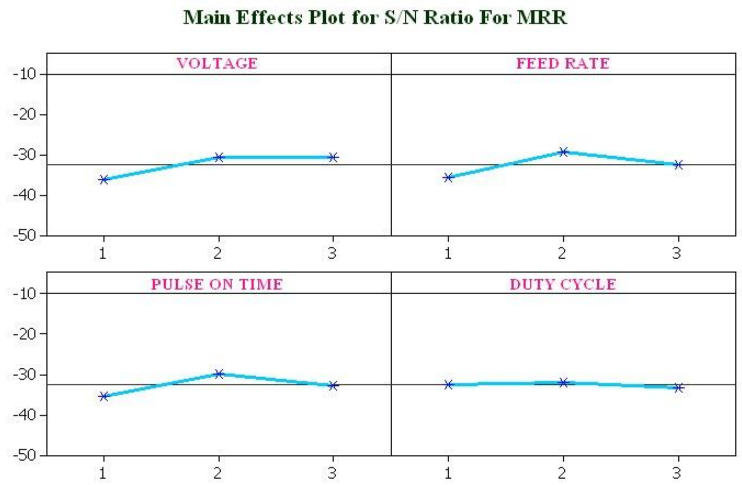

Fig. 5 Main Effects Plot for (S/N Ratio) of MRR in PECM

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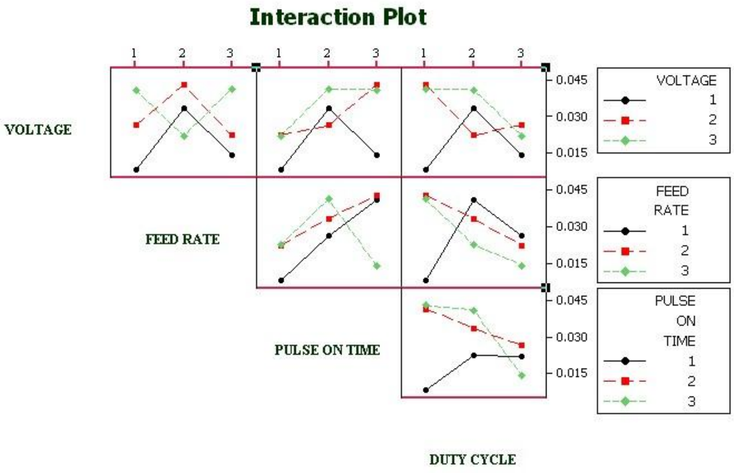

Fig. 6. Interaction effects

IV. ANOVA (Analysis of variance)

The relative magnitude of the effect of different factors can be obtained by the decomposition of variance; called analysis of variance (ANOVA).

ANOVA for (PECM):

$$\text{Overall Mean} = \bar{\bar{y}} = \frac{\sum\sum y_{ij}}{n_T}$$

$$\therefore \bar{\bar{y}} = \frac{(0.016 + \ldots\ldots + 0.083)}{18} = \frac{0.48}{18} = 0.0267$$

$$\text{Total Sum of Squares} = \text{SSTO} = \sum\sum\left(y_{ij} - \bar{\bar{y}}\right)^2$$

$$\therefore \text{SSTO} = \begin{bmatrix} (0.007 - 0.0267)^2 + (0.035 - 0.0267)^2 + \ldots\ldots \\ \ldots\ldots\ldots + (0.04 - 0.0267)^2 \end{bmatrix}$$

$$\therefore \text{SSTO} = 0.00222 \qquad\qquad (\text{DOF} = 17)$$

$$\text{Treatment Sum of Squares} = \text{SSTR} = \sum n_j\left(\bar{y}_j - \bar{\bar{y}}\right)^2$$

$$\therefore \text{SSTR}_A = \begin{pmatrix} \left(6 \times (0.0185 - 0.0267)^2\right) \\ + \left(6 \times (0.0307 - 0.0267)^2\right) \\ + (6 \times (0.0308 - 0.0267))^2 \end{pmatrix} = 0.000600333$$

Similarly,

SSTR_B = 0.000804333, SSTR_C = 0.000661833, SSTR_D = 0.000180333

Total Sum of Squares = SSTR_{All} =0.002246833

As we know, SSTO = SSTR + SSE

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SSTO=0.002246833+0.00005 = 320.9732 (verified)

$$\text{Mean Square} = \text{MS} = \frac{\text{SS}}{\text{DOF}}$$

$$\text{Error Mean Square} = \text{MSE} = \frac{\text{SSE}}{9} = \frac{0.00005}{9} = 0.00000556$$

$$\text{Treatment Mean Square} = \text{MSTR} = \frac{\text{SSTR}}{8}$$

$$= \frac{0.002246833}{8} = 0.000280854$$

$$\text{Variance} = \text{V} = \frac{\text{Sum of Squares}}{\text{Degrees of Freedom}}$$

$$\therefore \text{V}_\text{A} = \frac{\text{SS}_\text{A}}{\text{DOF}} = \frac{0.000600333}{2} = 0.000300167$$

F-test is used to determine which process parameters have a significant effect on the quality characteristic. The variance ratio denoted by F is given by;

$$\text{F} = \frac{\text{Mean Square of Factor ( )}}{\text{Error Mean Square}}$$

$$\therefore \text{F}_\text{A} = \frac{\text{MS}_\text{A}}{\text{MSE}} = \frac{\left(\frac{\text{SS}_\text{A}}{\text{DOF}}\right)}{\text{MSE}} = \frac{\left(\frac{0.000600333}{2}\right)}{0.00000556} = 54.03$$

Percentage Pooled Error (%p)

$$\%\,\text{p} = \frac{\text{Sum of Squares}}{\text{Total Sum of Square}}$$

$$\therefore \%\,\text{p}_\text{A} = \frac{\text{SS}_\text{A}}{\text{SSTO}} \times 100 = \frac{0.000600333}{0.00222} \times 100 = 26.99$$

Table 5. ANOVA

Parameter	DOF	SS	V	F	P (%)
A (Voltage)	2	0.000600333	0.000300167	54.03	26.99
B (Tool feed rate)	2	0.000804333	0.000402167	72.39	36.16
C (Pulse on time)	2	0.000589	0.0002945	53.01	26.48
D (Ultrasonic on time)	2	0.000180333	9.01667E-05	16.23	8.10
E(Error)	9	0.00005	5.55556E-06	1	2.24
Total	18				

The degree of freedom for the numerator is two and for the denominator nine. From the table of F-values;

$$F_9^2(95\%) = 4.26$$

$$F_9^2(99\%) = 8.02$$

The variation range is calculated by means of the equation

n_e is the number of repetitions to determine the mean values, such as A_1 and A_2.

$$\sqrt{F_9^2(95\%) \times \frac{V_e}{n_e}}$$

$$n_e = \frac{\text{Number of All Measurment Values}}{\text{No. Of DOF for factor( ) + No. of DOF for Mean Value}}$$

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$$\therefore 95\%\ \text{C.I.} = \pm\sqrt{4.26 \times \frac{0.0000056}{6}} = \pm 0.001986063$$

$$\text{and}\ \ 99\%\ \text{C.I.} = \pm\sqrt{8.02 \times \frac{0.0000056}{6}} = \pm 0.002725055$$

From the figure of Main Effect Plot, the optimum factor combination; A2B2C2D2

The process mean value is achieved by means of the equation (neglecting insignificant factors):

$$\mu = \left(A_3 - \bar{\bar{y}}\right) + \left(B_1 - \bar{\bar{y}}\right) + \left(C_2 - \bar{\bar{y}}\right) + \left(D_1 - \bar{\bar{y}}\right) + \bar{\bar{y}}$$

$$\therefore \mu = A_3 + B_2 + C_2 + D_2 - 3\bar{\bar{y}}$$

$$\therefore \mu = 0.0308 + 0.0352 + 0.0338 + 0.0260 - 3(0.0267)$$

$$\therefore \mu = 0.045833333\ \text{g/min}$$

Further it is possible to know in which range 95% of the values are to be expected for the optimum. The process average ‘x’ is given by the following equation:

$$x = \mu \pm \sqrt{F_9^2(95\%) \times V_e \times \left(\frac{1}{n_e} + 1\right)}$$

n_e takes the following value:

$$\frac{1}{n_e} = \frac{1(\text{for } \bar{\bar{y}}) + 2(\text{for A}) + 2(\text{for B}) + 2(\text{for C}) + 2(\text{for D})}{18} = \frac{9}{18}$$

$$\therefore x = 0.045833333 \pm \sqrt{4.26 \times 0.0000056 \times \left(\frac{9}{18} + 1\right)}$$
$$= 0.045833333 \pm 0.00598\ \ \text{g/min}$$

$$\therefore x = 0.045833333 \pm \sqrt{8.02 \times 0.0000056 \times \left(\frac{9}{18} + 1\right)}$$
$$= 0.045833333 \pm 0.008207\ \ \text{g/min}$$

Mean change = 0.0458 and S/N Ratio= (30.2662)

V. CONCLUSION

The aim of the present investigation is to design and develop PECM set-up and study the parametric effect on the responses such as: (i) MRR, thus the optimum parametric conditions are A3B2C2D2. The results show that the MRR improved by 32.35 % (0.034 g/min - 0.045g/min) in PECM with stationary tool. Thus PECM showed significant enhancement in MRR.These results open up the possibility of improving material removal rate with (i) tool design, (ii) selection of different process parameters in PECM for (INCONAL Super alloy-718)).

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