Analyze and optimize the Process Parameters of Electrochemical Machining of Ti6Al4V Using Orthogonal Array (OA8)

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Abstract - *With the rapid growth of aerospace performance, the machining quality and dimensional accuracy of aerospace parts is becoming important. To obtain excellent dimensional performance diaphragms of shafts turn more complex. In addition, because of their high strength, high temperature stability and corrosion resistance titanium alloys have found wider applications in aero-engine blade materials for which traditional machining methods fetch poor surface results. Electrochemical Machining (ECM) is an unconventional machining process in which there is no residual stress in the material. Also the machining quality and dimensional accuracy are increased. The thesis deals with main issues concerning ECM process parameters such as machining voltage, inter-electrode gap, processing time, temperature, stirring speed and flow rate. Process parameters are carried out as one-factor-at-a-time approach to analyze their effect on removal rate. Once their response is strong a DOE technique is chosen for optimization. Orthogonal array (OA8) involves eight treatment conditions of seven factors against response. Dominant level of each factor is determined. Strongest factors are chosen at their dominant levels for conformation run. The results are found to be in accordance with the one obtained from theoretical calculations. Factors that have strong effects at dominant level are yielded higher machining rate around 37.66 µ/min and surface roughness (R_a) around 0.13 µm.*

Keywords- *Electrochemical Machining, Ti6Al4V alloy, Orthogonal Array (OA8), Surface Roughness(R_a)*

I.INTRODUCTION

Titanium and its alloy have over the years proven to be technically superior and cost effective materials for a wide range of applications widening itself from aerospace, marine and automobile products because of their superior properties like high strength to weight ratio, excellent resistance to corrosion and torsion. The attractive properties of titanium alloys have facilitated in their enhanced use in spectrum of critical applications. However components with complex specifications still threw mechanical challenge in case of finishing processes.

With the advent of sophisticated machineries with multi axial machining capability, complex geometries are fabricated with high precision. But in case of titanium alloys due to their high strength to weight ratio the cutting and surface machining is very critical. Even with sophisticated surface machining equipment the production of components with low surface roughness less than 8 micrometer with high surface integrity still remains a challenge. Surfaces with minimal damage are desirable for critical components with fatigue performance, but such demands are difficult to be met by their conventional milling operations. Hence the inclusion of post milling polishing processes is unavoidable to address the challenges faced in production of critical components.

II. PROCESS PARAMETERS AND ITS INFLUENCES

Being a complex process, it is very difficult to determine optimal parameters for improving cutting performance. Metal removal rate and surface roughness are the most important output parameters, which decide the cutting performance. There is no single optimal combination of cutting parameters, as their influences on the metal removal rate and the surface roughness are quite opposite.

As in each case there are certain factors that influence the rate of a reaction. The required shape of the material to be processed is determined by the following factors:

A. Influence of Inter-Electrode Gap (IEG):

If the Inter-Electrode Gap is maintained smaller, the current flow into the electrolyte exponentially increases; as a result improved machining rate and better precision could be accomplished. This led to the deployment of Electrochemical machining of MEMS components.

B. Influence of Supply Voltage:

An external electric supply is used as a driving potential between the electrodes. The supply can either be continuous DC or pulsed DC. The increasing polarisation of work piece may impede its dissolution. This can be reduced by pulsed voltage. Experimental investigation on the influence of ECM parameters on material removal rate and accuracy recommends machining voltage range of 3-7V.

C. Influence of Stirring Speed:

The effect of stirrer in ECM is highly influential. Stirrer serves bi-functionally of which, the prime function is to remove the periodic sludge formed near anode as a result of anodic dissolution. The other function is to avoid the build-up of heat during chemical reaction. The undesired increase in temperature affects the concentration of electrolyte bath and thereby the electrolyte conductivity.

D. Influence of Machining Duration:

Machining time more dominant for evolution of machined profile. Especially for conformal cathode a considerable amount of time is required to create step-like formation on the anode. The response on the anode can be felt after few hours only. Pulse on time itself has its significant effect over the response.

E. Influence of Concentration of Electrolyte:

Electrochemical machining gives high material removal rates with good surface finish for titanium alloys. The oxide formed on the surface layer of titanium must be removed. A number of electrolytes can be used for material removal. But these often lead to surface irregularities. Pits, ridges and other defects formed on the electrochemically machined surface result in expensive post-machining polishing. Therefore an electrolyte that is operable for one titanium alloy may not be operable for other. Hence the electrolyte and its concentration play a predominant role on the response.

F. Influence of Electrolyte Temperature:

The electrolyte temperature is the important parameter which is done by heating the electrolyte bath and the temperature has to be monitored by thermometer frequently. It is important to maintain the constant temperature level. It may influence to higher material removal rate of work piece.

III. EXPERIMENTAL SETUP

The objective of the experiment is to optimize the process parameters. So the process is subjected to extensive trial and error experiments. Before the actual start of a series of treatments it is important to fix some of the parameters while the other is varied over a defined range. Refer Fig.1

Cathode : Bronze
Anode : Titanium alloy
Electrolyte: 3M NaF + 3M $NaNO_3$
Duration : 30 minutes

III a. EXPERIMENTAL PROCEDURE

a) The initial weight of anode is measured in grams by Schimadzu microbalance. Titanium is masked on all sides except for a square centimetre area by a Lacquer.

Fig.1 *Electro Chemical Machining Setup*

b) Bronze is connected to the negative terminal and titanium is given positive terminal. The electrodes are kept facing each other. It is ensured that unmasked area is completely dipped into the solution.

c) Inter-Electrode Gap(IEG) is maintained between the electrodes. Driving potential is turned on. Multimeter is used to ensure the flow of current.

d) The bath is kept over stirrer. Paddle starts to rotate according to stirrer speed. The machining is carried out for different stirrer speeds and supply voltages for duration of 30 minutes.

e) The loss in weights after machining is determined from micro balance after the lacquer was unmasked.

As the initial and final weights are known material removal rate can be determined from density of titanium.

III b. MATERIAL REMOVAL THICKNESS

Material removal rate was calculated from the weight loss of the anode.

Density of titanium = $4560\ kg/m^3$
= $4.56\ g/cm^3$
Density = mass / volume
= mass / (area * thickness)
Thickness = mass / (area * density)
For a material removal of 1mg & Exposed area = $1\ cm^2$
Thickness removed = $1mg / (1cm^2 * 4.56\ g/cm^3)$
= 2.19μm

*So, 'x' mg of material removal thickness = 2.19 * x µm*

IV. ORTHOGONAL ARRAY

Orthogonal arrays are simplified method of putting together an experiment. In an orthogonal array the levels were designated by 1 and 2. To determine the appropriate orthogonal array:

a) Number of factors and their levels should be defined
b) Degrees of freedom should be determined
c) Orthogonal array should be selected

A. Factors and Their Levels:

The effect of five different factors is determined against material removal. The bath volume consists of 300ml of Electrolyte. However for an area of 1 cm^2 200ml of solution might be sufficient. So these could also be chosen as factors.

Parameters	High level	Low level
Factor A - Inter Electrode Gap	3cm	5cm
Factor B - Supply Voltage	3V	5V
Factor C - Temperature of Electrolyte	30^0C	50^0C
Factor D - Molar Concentration	2M:2M	3M:3M
Factor E - Machining area	1cm^2	2cm^2
Factor F - Volume of electrolyte	200ml	300ml
Factor G - Machining duration	30mins	60mins

Table.1 *Factors and their levels*

B. Degrees of Freedom:

Degrees of freedom are used to determine the number of treatment conditions.

Degrees of freedom =(Number of levels-1) for each factor + (Number of levels-1)(Number of levels-1) for each interaction + One for average.

Degrees of freedom = 7(2-1) + 1 = 8. (OA8)

TC	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**MRR (µ/min)**
1	1	1	1	1	1	1	1	
2	1	1	1	2	2	2	2	
3	1	2	2	1	1	2	2	
4	1	2	2	2	2	1	1	
5	2	1	2	1	2	1	2	
6	2	1	2	2	1	2	1	
7	2	2	1	1	2	2	1	
8	2	2	1	2	1	1	2	

Table.2 *Template for Orthogonal array (OA8)*

Thus a total of 8 treatment conditions are taken for 7 chosen factors along different columns. Hence the orthogonal array is OA8. 1 and 2 represent the factors and their corresponding low and high levels respectively. Template is given in such a way that least amount of change occurs in the column on the left. Treatment Condition1 is composed of all level 1s. So it could thereby represent the normal conditions. This arrangement could provide the team with capability to assign factors with long setup times for those columns.

TC	**A 1**	**B 2**	**C 3**	**D 4**	**E 5**	**F 6**	**G 7**	**MRR (µ/min)**
1	3	3	30	2:2	1	200	30	2.667
2	3	3	30	3:3	2	300	60	16.61
3	3	5	50	2:2	1	300	60	33.1
4	3	5	50	3:3	2	200	30	35.5
5	5	3	50	2:2	2	200	60	15.04
6	5	3	50	3:3	1	300	30	15.7
7	5	5	30	2:2	2	300	30	3.212
8	5	5	30	3:3	1	200	60	22.74
							T = 18.08	

Table.3 *Orthogonal array and Results of Material Removal Rate*

The factors are maintained at the levels given by OA8 template to obtain material removal rate. Results from the table infer that material removal rate is maximum for Treatment Condition 4.

V. EFFECT OF EACH FACTOR AND ITS EFFECTS

Alphabets indicate corresponding factors and the suffix integer represents their respective levels. The effects of different factors are determined by taking average of all the responses at their lower and higher levels respectively

Factor A:

$A_1 = (2.667+16.61+33.1+35.55)/4 = 21.98$µ/min

$A_2 = (15.04+15.7+3.212+22.74)/4 = 14.173$µ/min

Increasing the Inter-Electrode Gap (IEG) from 3 cm to 5cm brings down the material removal rate from 21.98 to 14.173µ/min. So to increase the removal rate IEG should be maintained at 3cm.

Factor B:

B1 = (2.667+16.61+15.04+15.7)/4 = 12.5 µ/min

B2 = (33.1+35.55+3.212+22.74)/4 = 23.65µ/min

Increasing Voltage results in increasing the material removal rate. Better rate(23.65µ/min) is achieved at 5V only.

Factor C:

C1 = (2.667+16.61+3.212+22.74)/4 = 11.3µ/min

C2 = (33.1+35.55+15.04+15.7)/4 = 24.84µ/min

Temperature is the factor here. When the temperature is raised to 50·C removal rate gets doubled.

Factor D:

$D_1 = (2.667+33.1+15.04+3.212)/4 = 13.5$µ/min

$D_2 = (16.61+35.55+15.7+22.74)/4 = 22.65$µ/min

3M NaF: 3M NaNO$_3$ deserves to be the electrolyte concentration as it is evident from the results obtained.

Factor E:

E1 = (2.667+33.1+15.7+22.74)/4 = 18.55µ/min
E2 = (16.61+35.55+15.04+3.212) = 17.6µ/min

When the area is increased its effect doesn't appear to have great influence over the response as there is negligible difference between the two levels.

Factor F:

F1 = (2.667+35.55+15.04+22.74)/4 = 18.99µ/min
F2 = (16.61+33.1+15.7+3.212)/4 = 17.15µ/min

There isn't much difference between the removal rates for different bath volumes. So this mayn't give strong effect.

Factor G:

G1 = (2.667+35.55+15.7+3.212)/4 = 14.26µ/min
G2 = (16.61+33.1+15.04+22.74)/4 = 21.87µ/min

Machining duration is taken as factor G. A difference of 7.61µ/min is observed when the processes were carried out for 30 minutes and 60 minutes.

Va. FACTORS WITH STRONGEST EFFECTS

Values from the preceding calculations are placed in a response table. The absolute difference between level 1 and level 2 is calculated. A response graph is calculated to visualize the strong effects. The graph is plotted with the largest difference on the left and the smallest difference on the right.

Table.4 *Response Table for Material Removal Rate*

	A	B	C	D	E	F	G
L1	21.98	12.5	11.3	13.5	18.55	18.99	14.26
L2	14.17	23.65	24.84	22.65	17.60	17.15	21.87
Δ	7.80	11.15	13.54	9.15	0.95	1.84	7.61

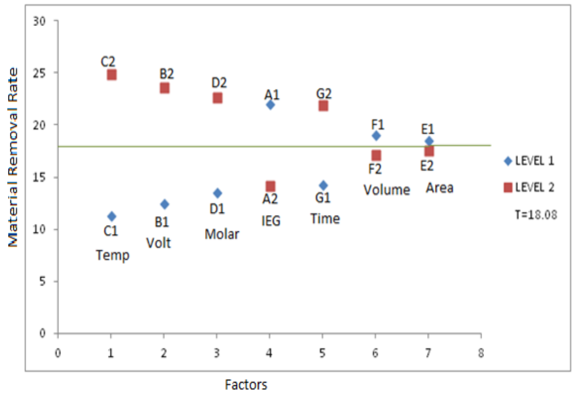

Fig. 2 *Factors Vs Material Removal Rate(µ/min)*

Differences in material removal rate for any factor between its two levels are greatest for bath temperature (factor C, Δ =13.54). Half of its Δ=6.77. So whichever the factor whose Δ is equal to or greater than 6.77 are considered to be strong effects. But the objective is to optimize the parameters by increasing the material removal rate. So the strong factors and their levels are A_1, B_2, C_2, D_2 and G_2.

Strongest effect is temperature for which Δ=13.54µ/min. So other dominant factors of the experiment are:

Voltage for which Δ = 11.15µ/min
Concentration for which Δ = 9.15µ/min
IEG for which Δ =7.807µ/min
Duration with Δ = 7.61µ/min

T=∑ y / n= =(2.667+16.61+33.1+35.5+15.04+15.7+3.212+22.74) /8
= 18.08µ/min

Vb. CONFORMATION RUN

A fundamental part of Taguchi approach is conformation run. To predict the outcome of the conformation run using:

MRR = A1 + B2+ C2 + D2 +G2 – (N-1)
= 21.98 + 23.65 + 24.84 + 22.65 +21.87 – (4*18.08)
= 42.64µ/min

Where,
MRR **-** is the estimate of response and
T **-** Overall average of the response data

In the conformation run dominant factors such as voltage, temperature, concentration and duration are maintained at level 2while area, volume and gap are at level 1.

For the same treatment condition obtained from strongest effects of factors the process was carried for 3cm IEG, 5V supply at 50°C for 1cm^2 area of 200ml electrolyte volume for 1 hour period.

Table 5. *Material Removal Rate at factor chosen by (OA8)*

TC	A	B	C	D	E	F	G	MRR (µ/min)
1	3	5	50	3:3	1	200	60	37.66

The conformation run gives removal rate about 37.67µ/min. According to the calculations the material removal rate is 42.64µ/min. Even the treatment condition 4 for which the factor area and time are alone reversed gave 35.55µ/min.

However in this case material removal rate was 37.67µ/min. The result is much closer to the one obtained from calculation.

VI. MORPHOLOGICAL ANALYSIS

The AFM figure for Titanium alloy was carried out before the process and after completion of Electrochemical Machining process. The obtained process parameters are adopted in this experiment. The surface roughness is identified to be less than 200nm in the Morphological analysis. Also the surface roughness was inspected for the same sample using mitutoyo surface roughness tester sj-410. It reads the surface roughness value as 0.128 µm.

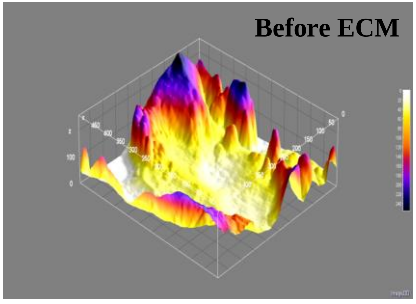

Fig. 3 *AFM Results before ECM Process*

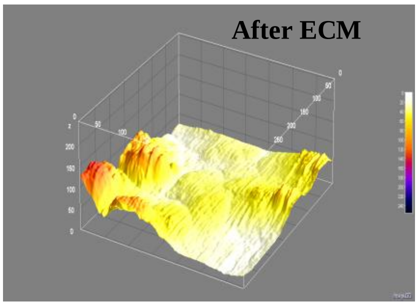

Fig. 4 *AFM Results after ECM Process*

VII. CONCLUSION

ECM process is subjected to extensive trial and error treatments. From the data collected project started with analyzing factors one-by-one right from stirrer speed, voltage and IEG to machining area and duration. Once the influence of each of these factors is determined it is important to optimize the test results. But as the experiments were carried out as one-factor-at-a-time approach a technique called Orthogonal Array (OA8) is used. Seven factors were chosen for eight treatment conditions according to the template. The process is run for those treatment conditions to obtain the collective response of all the factors.

Factors that influence strongest effect on the removal rate are determined. Conformation run is a fundamental part of Taguchi approach. For the strongest levels of dominant factors removal rate is increased than those obtained for different treatment conditions. An experiment is conducted for conformation. Removal rate is found to be increased.

A. Optimized Results:

Supply voltage = 5V
Inter-Electrode Gap (IEG) = 3cm
Bath Temperature = 50 °C
Electrolyte Concentration = 3M NaF and 3M $NaNO_3$
Duration = 60 Minutes
Volume of electrolyte = 200 ml
Machining area = 1 cm^2

Optimized Material Removal Rate for Parameters at these levels is **37.66µ/min** and surface roughness for the work piece is **0.128 µm.**

VIII.REFERENCES

[1] Besterfield.H., “Total Quality Management”, 3rd Edition, 2005.

[2] Bhattacharyya.B.,Munda.J., “Experimental investigation on the influence of electrochemical machining parameters on machining rate and accuracy in micromachining domain”, International Journal of Machine Tool and Manufacture, Vol. 43, 2003.

[3] Bhattacharyya.B.,Munda.J., Malapati.M., “Advancement in electrochemical micro- machining”, International Journal of Machine Tool and Manufacture, Vol. 44, 2004.

[4] Clark.W.G., McGeough.J.A., “Temperature distribution along the gap in electrochemical machining”, Journal of Applied Electrochemistry, Vol. 7, 1977.

[5] Chan Hee Jo, Bo Hyun Kim, “Micro electrochemical machining for complex internal micro features”, CIRP Annals-Manufacturing Technology, Vol. 58, 2009.

[6] Cliffon,D., Mount,A,R., Alder,G,M., and Jardine,D., “Ultrasonic measurement of the inter-electrode gap in electrochemical machining”, International Journal of Machine Tool and Manufacture, Vol 42, 2002.

[7] Datta, M., and Landolt, D., "Fundamentals aspects and applications of electrochemical micro fabrication", Journal of ElectrochimicaActa, Vol. 45, 2000.

[8] Douglas C.Montgomery, ”Design and analysis of experiments”, 7th Edition, 2012.

[9] Groover,M,P.,“Fundamentals of Modern Manufacturing” New York: John Wiley & Sons, 2006.

[10] Hocheng.H.,Y.H. Sun., S.C. Lin., P.S. Kao., “A Material removal analysis of electrochemical machining using flat end cathode”, Journal of Material Processing Technology, Vol. 140, 2003.

[11] JoaoCirilo da Silva Neto., EvaldoMalaquias da Silva., MarcioBacci da Silva., “Intervening variables in electrochemical machining”, Journal of Material Processing Technology, Vol. 179, 2006.

[12] Klocke.F., Zeis.M., Klink.A., Veselovac.D., “Experimental Research on the Electrochemical Machining of Modern Titanium- and Nickel-based Alloys for Aero Engine Components”, CIRP Journal of Manufacturing Science and Technology, Vol. 6, 2013.

[13] Ningsong Qu., Xiaolong Fang., Wei Li., YongbinZeng., Di Zhu., “Wire electrochemical machining with axial electrolyte flushing for titanium alloy”, Chinese Journal of aeronautics, Vol. 26, 2013.

[14] McGeough.J., “Theory of Electrochemical Machining”, 2005

[15] Ruszaj.A., “Investigations aiming to increase electrochemical machining accuracy “ Precision Engineering, Vol. 12,1990.