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Statistical Analysis of Response Parameters during Electro-Chemical Discharge Machining of Crystal Glass

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ABSTRACT : *We report on the electrochemical discharge machining (ECDM) on crystal glass with sodium hydroxide as an electrolytic medium which is a strong base and also a better conducting medium. The three control factors namely voltage, electrolyte concentration and inter-electrode gap were considered with three different levels for conducting the machining and the response parameters studied were Material removal rate (MRR) and Radial overcut (ROC). The Taguchi technique with L9 orthogonal array was used to design the experimental plan. The significance of each process parameter was evaluated by ANOVA and the design of experiments and analysis are carried out using Minitab. Artificial neural network (ANN) was employed to predict the response parameters. It was found that the voltage plays a significant role in achieving greater MRR followed by electrolyte concentration and inter-electrode gap.*
Keywords – *Crystal Glass, ECDM, MRR, ROC, ANN, ANOVA.*

I. INTRODUCTION

Nowadays, non-conventional machining practices are being taken into an advantage in order to remove excess material from very hard and fragile materials. Electric Discharge Machining (EDM) and Electro-Chemical Machining (ECM) were introduced to come across the necessities of manufacturing industries to machine advanced materials which are having the property of electrical conductivity. But, the materials like glass, ceramics, fiber reinforced composites and so on, which are electrically non-conductive in nature, hybrid machining processes are being established. HMPs combine the features of many conventional as well as non-conventional machining processes which help in attaining superior machining capabilities i.e. blending the benefits of diverse machining processes. The ECDM is a process which involves a complex combination of the electrochemical reaction and electro-discharge action.The electrochemical reaction helps in generation of the positively charged ionic gas bubbles, e.g. hydrogen. The electrical discharge action takes place between the tool and the workpiece due to the breakdown of the insulating layer of the gas bubbles as the DC power is supplied between the tool (or cathode) and the anode, resulting in material removal due to the melting, vaporization of the workpiece material and mechanical erosion.

B. Bhattacharyya et al conducted experiments with ECDM on non-conductive ceramic materials and discussed the influence of electrolyte concentration, voltage and tool tip geometry on material removal rate (MRR) and condition of the machined surface [1]. Shilpi Sharma et al. studied on the effective parameters of ECDM with their specific role in MRR, surface finish and TWR. The authors have summarized the different optimizing methods for achieving enhanced optimum conditions [2]. Zhi-Ping Zheng et al., worked on the 3D machining of Pyrex glass. Pulse voltage, rotational rate and travel rate of the tool are taken as input parameters. They have found that the accuracy of machining was found to be increased with increase in the rotational rate. This is due to the fact that, discharge was spread uniformly by the effect of centrifugal force [3]. Lijo Paul et al., studied on the effect of control factors on ECDM of boro-silicate glass. DOE was developed to conduct the experiments. Voltage, duty factor and concentration are taken as control factors and the best values were obtained at a voltage of 60V, electrolyte concentration of 30 % wt and a duty factor of 70% using Taguchi method of optimization. These three values are the best values to diminish the ROC [4]. Dhanvijay et al. worked on the tool mechanisms and made the comparison between electrolyte flow method and stagnant method. Voltage, electrolyte concentration, duty factor and pulse on time were taken as input parameters. They have concluded that using SS tool and electrolyte flow method has a high MRR of 0.72 mg/min with high DOC of 0.860 mm. In one combination DOC amplified primarily but remained unchanged in the range of 60V to 65V with the stagnant electrolyte using the copper tool but on the other hand, reverse effect was observed for SS tool [5]. Liu et al. conducted experiments on Aluminium 359 with 20% SiC (10 mm thick) with steel (ø 5 mm) as tool material. Sodium nitrate solution with a concentration ranging between 1 to 1.6 wt% was used as an electrolyte. The outcomes of the experiments exhibited that a raise in the current, duty cycle, pulse duration and electrolyte concentration would promote the occurrence of arcing action in ECDM. Also, they have concluded that the volume of an eroded crater of ECDM was less than that of EDM [6]. Harugade et al., The authors used a standard L9 orthogonal array for conducting experiments, S/N ratio was performed to study the contributions of machining parameters. Soda lime glass was used as workpiece material and copper as tool material with KOH and NaCl as the electrolyte. Voltage, electrolyte concentration and IEG were considered as input parameters. They have concluded that, voltage as a significant factor followed by electrolyte concentration and inter-electrode gap. Also, KOH is the best electrolyte compared to NaCl in achieving high metal removal rate of soda lime glass [7].

II. EXPERIMENTATION

The fig.1 shows the schematic diagram of Electrochemical Discharge Machining. It consists of cathode (tool), anode (electrode), power supply unit. Initially, the workpiece is clamped on to the work table and the stand-off distance maintained is constant i.e. 0.03 mm. The tool can be moved in a vertical direction by rotation the handle. The arrangement used is rack and pinion set for the movement of tool in the vertical direction.

Constant Parameters	
Tool(cathode)	Copper wire (Ø1 mm)
Anode	Copper plate (100 mm × 50 mm × 6 mm)
Electrolyte	Sodium hydroxide (NaOH)
Work piece	Crystal glass
Stand of Distance	0.03 mm
Time	20 minutes

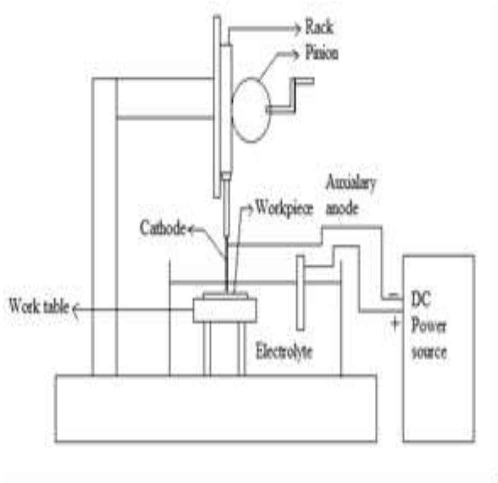

Fig. 1 Schematic Diagram of Electro Chemical Discharge Machining

Fig. 2 Pictorial view of ECDM

2.1 Mechanism of material removal & Spark generation:

The ECDM process comprises of an intricate mixture of the ECM and EDM. The positively charged ionic gas bubbles usually hydrogen bubbles are produced due to the electrochemical reaction. The electrical discharge action takes place between the tool and the workpiece due to the failure of the non-conducting layer of the gas bubbles. As the DC power supply voltage is applied in between the tool (cathode) and the anode, consequences of melting and vaporization of the workpiece material which origins mechanical erosion and the material removal.

Table 1: Machining Conditions

Table 2: Control Factors and Their Levels Used In Experiment

Symbols	Factors	L1	L2	L3
A	Voltage (Volts)	50	60	70
B	Electrolyte concentration (%)	10	15	20
C	Inter-Electrode Gap (mm)	20	30	40

2.2 Design of Experiments using Taguchi Method

The objective of an experimental activity is to acquire the supreme facts of a system with the less number of trials. A designed experiment is a succession of runs, or tests, in which we persistently vary the input variables at the same time and spot the responses [8]. In research related works, designed experiments can be used in exploring those process parameters which affects the quality of a product. After that, we are upgrading input factors to enrich a product's manufacturability, consistency, superiority and field performance.

2.3 Selection of Orthogonal Array.

Taguchi designs use orthogonal arrays, which evaluates the effects of factors on the response mean and variation. The DOFs for the experiment are calculated first to select an applicable OA. The applied voltage, electrolyte concentration and IEG are the three factors with three levels are considered. With three factors at three levels, the total DOF is calculated. From the values of DOF=7, it is concluded that at least seven trials are to be conducted to estimate the effects of each parameter. The standard OA which has at least three numbers of columns at three levels is selected. Hence, the selected standard OA is L9 which has three level columns and nine rows.

2.4 Signal to noise ratio

In Taguchi designs, a degree of toughness used to isolate the variable parameters that lessen unevenness in a product or process by reducing the effects of disturbances, technically termed as noise factors. In a Taguchi based DOE, it is possible to manipulate these noise factors to force variability in order to occur and form the results, identify optimal control factor settings that make the product robust i.e. variation from the noise factors. Higher values of the signal-to-noise ratio (S/N) recognize variable parameter settings that diminish the effects of the noise factors.

2.5 Analysis of Variance (ANOVA)

ANOVA is a statistical technique used to explore and model the correlation between output parameters and one or more individual variables. The involvements of distinct quality inducing factors are the critical key to the control to be required for a product design. One of the frequently employed statistical tools is ANOVA, which helps in examining the consequences obtained from the Orthogonal Array and determines the contribution of each influencing factor. Main effect plots review the contribution of individual parameters on response parameters. Also, it is possible to find out the interactions between the variable parameters

2.6 Artificial neural network (ANN)

The human brain affords evidence of the enormous neural networks that help us in getting our job done accurately and fruitfully. The human brain is capable of performing a wide range of tasks which may be either simple or complicated [9]. Working of the human brain is highly complicated which includes faster rates of data transfer, massive parallelism, and precise information processing ability. The artificial neural network works similar to that of the human brain. ANN is developed in order to solve the difficult problems and also the predicted the outcomes of a process depending on the inputs fed.

Various inputs to the neurons are represented by ‘Xn’ and each of these inputs are multiplied by a connection weighed which are represented by ‘Wn’ and added to the bias ‘φ’ to compute activation ‘an’ which is converted into the output ‘On’ via a transfer function.

It is difficult to for an individual neuron to process in some cases. In order to overcome this limitation, numbers of neurons are linked together in the form of layers to perform complicated tasks. A layer is defined as a group of parallel neurons with interactions between them.

III. RESULTS AND DISCUSSIONS

The experimental work was conducted on crystal glass with three input parameters and three levels.

Table 3: Experimental Outcomes Of MRR And ROC For Different Input Parameters

Trial No.	Voltage (volts)	Electrolyte Conc. (%)	IEG (mm)	MRR (mg/ min)	ROC (mm)
1	50	10	20	0.1863	0.053
2	50	15	30	0.2759	0.068
3	50	20	40	0.4537	0.089
4	60	10	30	0.3519	0.121
5	60	15	40	0.3891	0.136
6	60	20	20	1.3957	0.154
7	70	10	40	0.7294	0.142
8	70	15	20	1.5889	0.167
9	70	20	30	2.3842	0.193

Table 4: ANOVA For MRR

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% of contri.
Voltage	2	2.49022	2.49022	1.24511	35.49	0.027	54.15%
Electroly-te conc.	2	1.52102	1.52102	0.76051	21.68	0.044	33.07%
IEG	2	0.51712	0.51712	0.2585	7.37	0.119	11.24%
Error	2	0.07016	0.07016	0.03508			1.52%
Total	8	4.59852					99.58%

S = 0.1873   R-Sq = 98.5%   R-Sq(adj) = 93.9%

Experiments were carried out using a well-designed set of trials using DOE based Taguchi technique. Meanwhile, for three levels and three factors, L9 OA comprising of nine trials were employed. The consequence of process parameters such as voltage, electrolyte concentration and IEG on the material removal rate (MRR) and radial overcut (ROC) will be evaluated in order to gain the finest machining conditions for the attainment of higher MRR and lower ROC.W1 = Initial Weight (mg), W2 = Final Weight (mg), D= Diameter of hole (mm), d= Diameter of tool (mm).

$$MRR = \frac{(W_1 - W_2)}{t} \text{ mg/min}$$

$$ROC = \frac{(D - d)}{2} \text{ mm}$$

ANOVA was carried out using Minitab 14 and the outcomes are presented in Table 4. It is concluded that the probability of voltage parameter is 0.027 which is less than that of 0.05. The percentage of contribution of voltage is found to be 54.15% which is significantly greater than that of electrolyte concentration and IEG which are having the percentages of contribution 33.07% and 11.24% respectively. Therefore it is evidential that voltage is the chief influencing factor in accomplishing higher MRR [10].

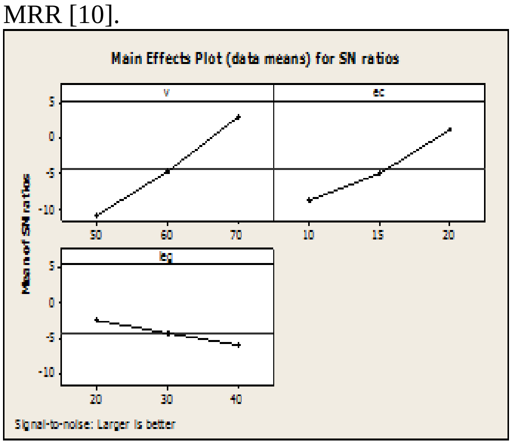

Fig. 3 Main effect plot for S/N ratio (MRR)

Fig. 3 gives us the information about the main effect plot for S/N ratio of MRR. It is observed that mean value is higher for voltage compared to that of electrolyte concentration and IEG. Hence it can be stated that voltage is the primary factor that impacts the MRR followed by electrolyte concentration and IEG. Also, it is seen from the graph that 70V, 20%, and 20mm are the optimal combinations of voltage, electrolyte concentration and IEG in achieving higher MRR.

Table 5: ANOVA For ROC

S = 0.005364   R-Sq = 99.7%   R-Sq(adj) = 98.7%

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% of contribution
Voltage	2	0.014883	0.014883	0.007441	258.58	0.004	85.6%
Electrolyte conc.	2	0.002406	0.002406	0.001203	41.80	0.023	13.84%
IEG	2	0.000038	0.000038	0.000019	0.65	0.605	0.21%
Error	2	0.000058	0.000058	0.000029			0.33%
Total	8	0.017384					

The outcomes of ANOVA achieved by Minitab 14 are presented in Table 5. It is concluded that the probability of voltage parameter is 0.004 which is less than that of 0.05. The percentage of contribution of voltage is found to be 85.6% which is significantly greater than that of electrolyte concentration and IEG which are having the percentages of contribution 13.84% and 0.21% respectively. Therefore it is evidential that voltage is the chief influencing factor in accomplishing higher MRR.

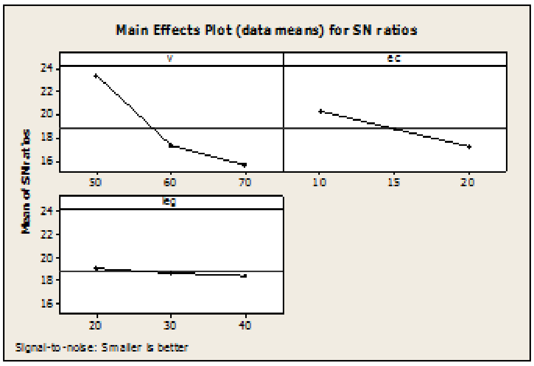

Fig. 4 Main effect plot for S/N ratio (ROC)

Radial overcut is the difference in the dimension of the electrode, and the dimension of the cavity produced during the process [11]. Fig 4 depicts the information about the main effect plot for S/N ratio of ROC. It is noticed that mean value is higher for voltage associated to that of electrolyte concentration and IEG. Hence it can be specified that voltage is the principal factor that influences the MRR followed by electrolyte concentration and IEG. Also, it is seen from the graph that 50V, 10%, and 20mm are the optimal combinations of voltage, electrolyte concentration and IEG in achieving smaller ROC.

Table 6: Evaluation between Experimental Values And ANN Predicted Values

Trial no.	Exp MRR (mg/min)	ANN predicted MRR (mg/min)	Error (%)	Exp ROC (mm)	ANN predicted ROC (mm)	Error (%)
1	0.1863	0.21095	13.23	0.053	0.060206	13.59
2	0.2759	0.26295	4.69	0.068	0.063026	7.31
3	0.4537	0.45574	0.44	0.089	0.080254	9.82
4	0.3519	0.35967	2.2	0.121	0.12046	0.44
5	0.3891	0.38742	0.47	0.136	0.13725	0.91
6	1.3957	1.3972	0.10	0.154	0.15105	1.91
7	0.7294	0.71867	1.47	0.142	0.14573	2.62
8	1.5889	1.6179	1.82	0.167	0.16228	2.68
9	2.3842	2.3833	0.03	0.193	0.19248	0.26

The Table 6 indicates the evaluation between experimental MRR and ANN predicted MRR and evaluation between experimental ROC and ANN predicted ROC. It is witnessed from the plot that there exists very less deviation between the ANN values and experimental values [12, 13].

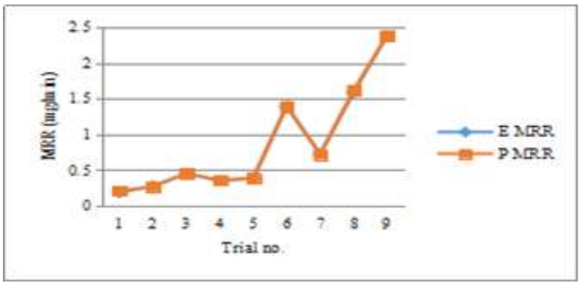

Fig.5 Plot of Experimental MRR and ANN predicted MRR

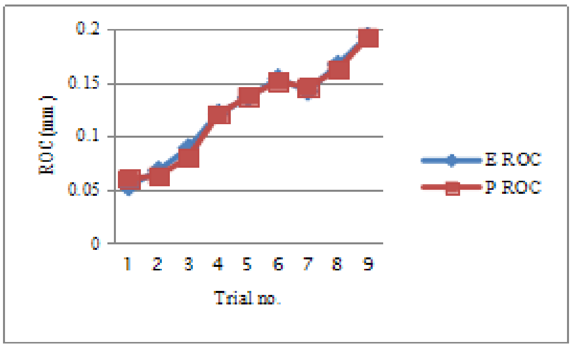

Fig.6 Plot of Experimental ROC and ANN predicted ROC

While doing ANN it is observed that the value of R2 is found equal to 99.32%. Therefore it is concluded that the value of R2 equal to 99.32% means that the ANN is best suited for determining the predicted values.

IV. CONCLUSION

- Higher MRR was achieved with the combination of 70V, 20% and 30mm. Therefore, the mentioned combination is preferred as the optimal combination.
- Minimum ROC was attained with the combination of 50V, 10% and 20mm and hence this is the optimal combination.
- From ANOVA it is depicted that voltage has the major percentage of contribution in attaining higher MRR and minimum ROC.
- MRR and ROC is found to be increased with increase in applied voltage and electrolyte concentration.
- IEG is treated as very less significant factor.
- The comparison between experimental results and ANN predicted results has shown that the predicted results are slightly deviated from the experimental results.
- R^2 value indicates that the accuracy of the results are best suited for prediction of response parameters.

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