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Electrochemical Discharge Machining of Non-Conducting Ceramics

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ABSTRACT

The electrochemical discharge machining (ECDM) process is mostly applied for machining non-conducting engineering ceramic materials, such as aluminium oxides, zirconium oxides, and silicon nitrides, etc. Experiments on ECDM have been carried out according to designed experimental plan based on standard orthogonal array (L_9) to identify the optimal parametric conditions of ECDM process using Taguchi method of parametric optimisation. In this study, the signal-to-noise (S/N) ratio and the ANOVA analyses are employed to find the relative contributions of the main machining parameters, such as applied voltage, electrolyte concentration and interelectrode gap in controlling the machining performance, such as material removal rate and radial overcut of the ECDM process. The confirmation of experimental results under optimal parametric condition are provided to ensure the improvement in quality characteristics of the ECDM process. The highly purified non-conducting zirconium oxide is used as workpiece material and aqueous *KOH* in stagnant condition as electrolyte with three different concentrations (i.e., 15 per cent, 25 per cent and 20 per cent). The applied voltage of pulsed d.c. power supply has three levels of 50 V, 60 V and 70 V and the three different inter-electrode gap setting considered for the experiments are 20mm, 30mm and 40mm respectively.

1. INTRODUCTION

The electrochemical discharge machining (ECDM) process is expected to have tremendous applications for machining non-conducting engineering ceramic materials, such as aluminium oxides, zirconium oxides, silicon nitrides, etc. Such non-conducting ceramic materials have wide industrial applications in bearings, computer parts, artificial joints, cutting tools, electrical and thermal insulators, electronic devices, aerospace components, etc. due to their superior properties, such as high compressive strength, high wear resistance, high strength-to-weight ratio and high hardness characteristics[1]. The present need of every industrial organisation is to improve the quality of its machining processes and reduce the cost continuously so as to compete on price and performance and to maintain profitability. To meet the commercial and the industrial requirement of ECDM of non-conducting ceramic parts, extensive research is needed to improve the quality characteristics of ECDM process through parametric design and optimisation analysis based on Taguchi method of robust design. The optimal quality characteristics, such as material removal rate (MRR) and radial overcut (ROC) of ECDM process can be achieved by controlling three important machining parameters, such as applied voltage, electrolyte concentration and interelectrode gap of ECDM process.

Some research on ECDM has been carried out for machining non-conducting aluminium oxide ceramic materials, and a good machining performance is

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obtained using aqueous *KOH* as electrolyte[2]. The electrochemical discharge machining of non-conducting zirconium oxide ceramic materials using aqueous *NaOH* is also reported, and a closer dimensional accuracy of machining with higher MRR is achieved[3].

2. FUNDAMENTALS OF ECDM PROCESS

ECDM is a combined process of electrochemical (EC) reaction and electrodischarge (ED) action. The EC reaction in the electrolyte solution helps in the generation of hydrogen gas and vapour bubbles. The ED action takes place between the tool and the workpiece due to breakdown of the insulating layer of gas bubbles when pulsed d.c. power supply voltage is applied between the tool (cathode) and the auxiliary electrode (anode). The tool is immersed in the electrolyte solution and the level of the electrolyte is controlled by the electrolyte supply unit and is kept just 2-3 mm above the tool tip. The auxiliary electrode is also immersed in the electrolyte. As the voltage is raised, quite violent sparking occurs[4]. The non-conducting workpiece material is placed at the sparking zone and the tool always touches the workpiece which is controlled by the gravity feeding arrangement. The sparking action results in material removal from the non-conducting engineering ceramics due to melting and vapourisation caused by the heat energy of spark discharge. An interelectrode gap between the tool and the auxiliary electrode is maintained during machining and that can be adjusted by interelectrode gap control device. The schematic diagram of ECDM system is exhibited in Fig. 1.

3. ECDM OF ZIRCONIUM OXIDE CERAMICS

3.1 Experimental Conditions

In the present investigation, the tool was made of copper of 2 mm diameter. The test workpiece specimens were made of highly purified zirconium oxide ceramic materials. The shape of the workpiece was circular and its diameter and thickness were 25mm and 3 mm, respectively. Aqueous *KOH* was used as stagnant electrolyte for experimentation. As the machining rate of ceramic is low, the machining time taken for the experiment was 45 min. The single phase pulsed d.c. power supply was used for this purpose. The drilling operation on the zirconium oxide ceramics was performed.

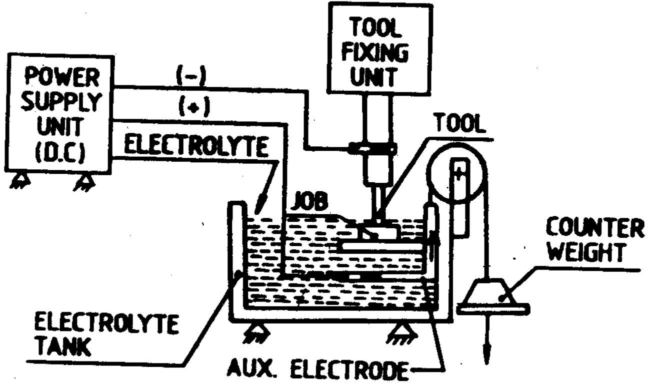

Figure 1. Schematic diagram of ECDM system

3.2 Selection of Machining Process Parameters

Experiments were performed using ECDM setup. The initial machining parameters were as follows: applied voltage (60V), electrolyte concentration (20 per cent *KOH* solution) and interelectrode gap (30 mm). After performing the basic experiments, it was found that the feasible range of applied voltage was 50-70 V, the electrolyte concentration range 15-25 per cent and the interelectrode gap range 20-30 mm. In the present parameter design, three levels of each machining parameters were selected (Table 1).

Table 1. Machining parameters and their levels

Symbol	Machining parameters	Level 1	Level 2	Level 3
A	Applied voltage (V)	50	60	70
B	Electrolyte Conc. (%)	15	20	25
C	Interelectrode gap (mm)	20	30	40

3.3 Measurement of Machining Performance

Experiments were conducted as per designed experimental plan and the performance or responses were measured for each experimental run. Here, MRR and ROC were taken as two performance criteria or responses. The amount of metal removed (MR) was measured by taking difference in weight of the specimen before (W_1) and after machining (W_2). The MRR can be evaluated as MR/t or $(W_1 - W_2)/t$, where t is the machining time. The outer ROC is computed as $(D - d)/2$, where D is the diameter of the drilled hole on specimen and d is the diameter of the tool.

4. TAGUCHI METHODOLOGY-BASED DESIGN & ANALYSIS OF MACHINING PARAMETERS

The present analysis includes Taguchi method-based parametric optimisation technique to quantitatively determine the effects of various machining parameters on the quality characteristics of ECDM process and to find the optimum parametric condition for obtaining optimum machining criterial yield. In this analysis, the parameteric design of experiment is performed based on the selection of an appropriate standard orthogonal array. The analyses of signal-to-noise (S/N) ratio and ANOVA were carried out to study the relative importance of the machining parameters on both MRR and ROC of ECDM process for machining non-conducting zirconium oxide ceramic materials. Based on S/N ratio and ANOVA analysis, the optimal setting of the machining parameters for MRR and ROC were obtained and verified.

4.1 Selection of Orthogonal Matrix Experiment

The total degrees-of-freedom (DOFs) for experiments is calculated first to select an appropriate orthogonal array for the experiment. The applied voltage, electrolyte concentration and interelectrode gap are the three factors and each factor has three levels considered for ECDM experiment. With three factors at three levels, the total DOFs is 7 [= 1+3×(3-1)]. In the present study, the interaction between the machining parameters is neglected. From the value of DOFs = 7, it is concluded that at least seven experiments are to be conducted to estimate the effects of each machining parameters. After knowing the value of total DOFs, the next step is to select an appropriate orthogonal array. The standard orthogonal array which has at least three number of columns at three levels, is selected. Hence, the selected standard orthogonal array is L_9 which has four three-level columns and nine rows. This array has total eight DOFs and it can handle four three-level machining parameters. Each machining parameter can be assigned to a column and nine machining-parameter combinations are available in L_9 orthogonal array matrix experiment. Therefore, only nine experiments are required to be conducted as per L_9 orthogonal array to study the effects of machining parameters on the performance of ECDM process. Since the L_9 orthogonal array has four columns, one column of the array is left empty for the error of experiments, and orthogonality is not lost by letting one column of the array remain empty.

4.2 Analysis of Signal-to-Noise Ratio

In Taguchi method, S/N ratio is used to measure the quality characteristics deviating from the desired value. The term signal represents the desirable mean value of the output characteristics and the term noise represent the undesirable value (i.e., standard deviation) for the output characteristics. In order to obtain optimal machining performance, the higher the better quality characteristics for MRR is considered. The S/N ratio for MRR, for jth experiment is defined as

$$\eta_j = -10 * \log_{10}\left(\frac{1}{m}\sum_{i=1}^{m}\frac{1}{y_{ij}^2}\right) \qquad (1)$$

where m is the number of replications and y_{ij} is the value of MRR of i^{th} replication test for j^{th} experimental condition.

Table 2 shows the experimental results for MRR and the corresponding S/N ratio using Eqn(1). Since the experimental design is orthogonal, it is possible to sort out the effect of each machining parameter at different levels. The mean S/N ratio for the applied voltage (A) at levels 1, 2 and 3 can be calculated by averaging the S/N ratios for the experiments 1-3, 4-6 and 7-9, respectively.

The average S/N ratio for all the levels of all machining parameters (factors) taking MRR as response is graphically exhibited in Fig. 2. The highest average S/N ratio gives the maximum MRR. It is clear from the S/N ratio response graph (Fig. 2) that for achieving maximum MRR, the optimum condition of machining is $A_3B_3C_1$, i.e., applied voltage of 70 V, electrolyte concentration of 25 per cent aqueous *KOH* and interelectrode gap of 20 mm. On the other hand, the lower the better quality characteristics for ROC is taken for obtaining optimal machining performance. The

Table 2. Design of experiments and experimental results for MRR and S/N ratio

	Design of experiments							
Expt. No.	Applied voltage, (V)	Electrolyte concentration (%)	Inter-electrode gap (mm)	MRR (mg/min)			Average MRR (mg/min)	S/N Ratio (dB)
j	A	B	C	y_{1j}	y_{2j}	y_{3j}	y_{4j}	
1	50	15	20	0.1860	0.1867	0.1874	0.1867	-14.58
2	50	20	30	0.2756	0.2750	0.2762	0.2756	-11.19
3	50	25	40	0.4530	0.4536	0.4533	0.4533	-6.87
4	60	15	30	0.3509	0.3514	0.3510	0.3511	-9.09
5	60	20	40	0.3889	0.3880	0.3898	0.3889	-8.20
6	60	25	20	1.3950	1.3960	1.3958	1.3956	2.90
7	70	15	40	0.7289	0.7294	0.7284	0.7289	-2.75
8	70	20	20	1.5884	1.5890	1.5893	1.5889	4.02
9	70	25	30	2.3838	2.3848	2.3846	2.3844	7.55

S/N ratio for jth experiment, *h* taking ROC as response, is defined as

$$\eta_j' = -10*\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_{ij}^2\right) \qquad (2)$$

where y_{ij} is the value of ROC for i^{th} test of replication for j^{th} experimental condition.

Table 3 shows the experimental results for ROC and the corresponding S/N ratio using Eqn (2). The mean S/N ratio for ROC for all the factors at different levels is determined. The S/N response graph for ROC is shown in Fig. 3.

The greater average S/N ratio corresponds to the minimum ROC. From the S/N response graph (Fig. 3), it is concluded that the optimum parametric

Table 3. Experimental results for ROC and S/N ratio

Expt. No.	Applied voltage, (V)	Electrolyte concentration (%)	Inter-electrode gap (mm)	MRR (mg/min)			Mean MRR (mg/min)	S/N Ratio (dB)
j	A	B	C	y_{1j}	y_{2j}	y_{3j}	y_j	
1	50	15	20	0.04	0.05	0.06	0.05	25.91
2	50	20	30	0.12	0.10	0.08	0.10	19.89
3	50	25	40	0.20	0.17	0.23	0.20	13.91
4	60	15	30	0.05	0.03	0.07	0.05	25.58
5	60	20	40	0.24	0.25	0.26	0.25	12.04
6	60	25	20	0.08	0.09	0.13	0.10	19.80
7	70	15	40	0.18	0.17	0.25	0.20	13.84
8	70	20	20	0.40	0.48	0.47	0.45	6.91
9	70	25	30	0.38	0.39	0.43	0.40	7.95

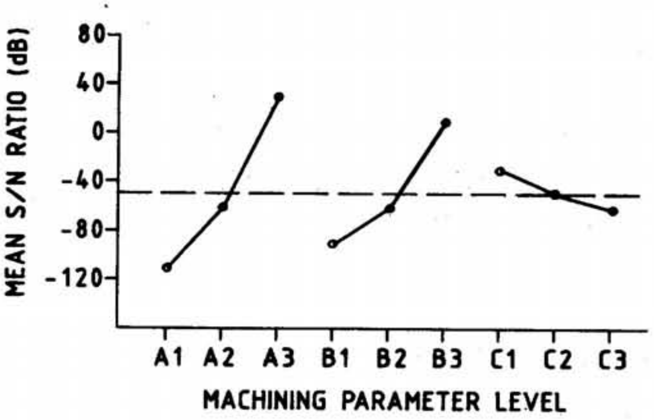

Figure 2. Signal-to-noise graph for material removal rate

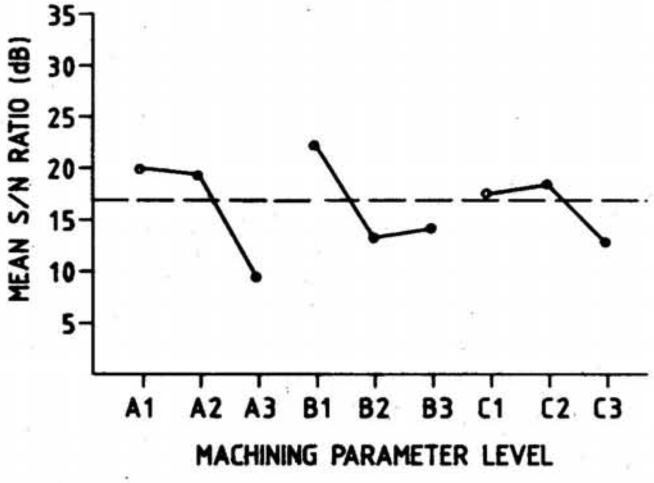

Figure 3. Signal-to-noise graph for radial overcut

combination is A_1 B_1 C_2, i.e., applied voltage of 50 V, electrolyte concentration of 15 per cent aqueous *KOH* and interelectrode gap of 30 mm.

4.3 Analysis of Variance

In this investigation, the analysis of variance[6] (ANOVA) is performed to determine which machining parameter significantly affects the quality characteristics of ECDM process and also to find the relative contribution of machining parameters in controlling the responses of the ECDM process. To accomplish ANOVA, the total sum of squared deviation (SS_T) from the total mean S/N ratio (h_m) can be determined as

$$SS_T = \sum_{j=1}^{N} (\eta_j - \eta_m)^2 \tag{3}$$

where N is the total number. of experiments and η_m is the grand mean of S/N ratio.

$$(SS_T) = \left(\sum_{j=1}^{N} \eta_j\right) / N \tag{4}$$

The total sum of SS_T is decomposed into two sources: (i) the sum of squared deviations due to each machining parameters (SS_A, SS_B and SS_C) and (ii) the sum of squared error (SS_E).

To perform F (variance ratio) test, the mean squared deviation due to each design parameter is calculated. The mean of squared deviation is equal to SS_T divided by the number of DOFs associated with the design parameters. The value of F for each design parameter is the ratio of the mean of the squared deviation to the mean of squared error. The percentage contribution by each of the design parameters is a ratio of the value of F of each design parameters to the total sum of values of F for all the design parameters. The results of ANOVA for MRR is shown in Table 4. The calculated value of F in ANOVA table is used to measure relative factor effects. The larger the value of F, the more important that factor becomes for controlling the responses of ECDM process. So the value of F can be used to rank order the contribution of factors. From the results of ANOVA, it is reflected that the applied voltage is the most influencing factor for controlling MRR. The electrolyte concentration has moderate effect on MRR. The interelectrode gap has very little effect on MRR of ECDM process. According to F test, the change in the design parameter has a significant effect on the quality characteristics if the calculated value of F is greater than the value of F_a (n_1, n_2), where (1-a) is the confidence level and n_1 and n_2 are the DOFs of design parameter and error, respectively[6]. Within 75 per cent confidence limits for n_1=2, and n_2=2, the value of $F_{0.25}(2,2)$ is 3. The calculated value of F for each design parameter is greater than 3. Hence at 75 per cent confidence level, the change in each design parameter has a significant effect on MRR.

Table 5 shows the results of ANOVA for ROC. It is also found that the applied voltage has the most significant effect on ROC of ECDM process. The electrolyte concentration has moderate effect on ROC. The interelectrode gap has very little effect on ROC compared to other machining parameters of ECDM

Table 4. Results of ANOVA for MRR

Symbol	Machining parameter	Degrees of freedom	Sum of squares	Mean squares	F	Contribution (%)
A	Applied voltage	2	287.87	143.935	133.644	62.76
B	Electrlyte concentration	2	153.43	76.715	71.23	33.45
C	Interelectrode gamp	2	17.43	8.715	8.092	3.79
Error		2	3.23	1.077		
Total		8	461.77			

Table 5. Results of ANOVA for radial overcut

Symbol	Machining parameter	Degrees of freedom	Sum of squares	Mean squares	F	Contribution (%)
A	Applied voltage	2	198.87	99.44	16.22	52.46
B	Electrlyte concentration	2	141.11	70.56	11.51	37.23
C	Interelectrode gamp	2	39.09	19.55	3.19	10.31
Error		2	12.26	6.13		
Total		8	391.33			

process. The contribution order of the machining parameters for ROC is applied voltage, electrolyte concentration and interelectrode gap which is similar for MRR. From the calculated value of *F*, it is concluded that at 75 per cent confidence level, all the machining parameter have significant effect on ROC as the calculated value of *F* is greater than the value of $F_{0.25}(2,2)$.

4.4 Confirmation Tests

After the selection of the optimal level of design parameters, the final step is to predict and verify the improvement in the quality characteristics of the ECDM process. The predicted optimum value of S/N ratio $\hat{\eta}_{opt}$ can be determined[7] as

$$\hat{\eta} = \eta_m + \sum_{j=1}^{p}\left(\bar{\eta}_j - \eta_m\right) \tag{5}$$

where η_m is the grand mean of S/N ratio, $\bar{\eta}_j$ is the mean S/N ratio at the optimum level, and p is the number of main design parameter that affects the quality characteristics.

The predicted S/N ratio using the optimal machining parameter for MRR can then be obtained and the corresponding maximum MRR can also be calculated using Eqn (1). Table 6 shows a comparison of the predicted MRR with the actual MRR using the optimal machining parameter and good agreement between the predicted and the actual MRR is observed. The increase in S/N ratio from the initial machining parameters to the optimal parameters is 12.523 dB which means that the MRR of ECDM process increases to four times of the initial value.

Table 6. Results of confirmation experiment for MRR

	Initial cutting parameter	Optimal machining parameters	
		Predicted	Experimental
Level	$A_2B_2C_2$	$A_3B_3C_1$	$A_3B_3C_1$
MRR (mg/min)	0.6044	3.192	(2.46, 2.58, 2.64)
S/N ratio	- 4.37	10.08	8.153

Improvement of S/N ratio = 12.523 dB.

Prediction error of S/N ratio = 1.927 dB.

Table 7. Results of confirmation experiment for radial overcut

	Initial cutting parameter	Optimal machining parameters	
		Predicted	Experimental
Level	$A_2\ B_2\ C_2$	$A_1\ B_1\ C_2$	$A_1\ B_1\ C_2$
ROC, mm)	0.125	0.044	(0.04, 0.05, 0.06)
S/N ratio, (dB)	18.06	27.09	25.91

Improvement of S/N ratio = 7.85 dB

Prediction error of S/N ratio = 1.18 dB

A comparison of the predicted ROC and the actual ROC using the optimal machining parameter is shown in Table 7. A predicted ROC is consistent with the actual ROC. The increase in the S/N ratio from the initial to the optimal machining parameters is 7.85 dB and therefore the improved value of ROC is 0.4 times of the initial value.

5. CONCLUSIONS

The Taguchi method of parametric optimisation is applied for the design optimisation of the machining parameters of ECDM process for hole drilling operation on non-conducting zirconium oxide ceramic components. From the experimental results, S/N ratio and ANOVA analysis and confirmation test results, the following conclusions are drawn:

(a) The applied voltage, electrolyte concentration and interelectrode gap are the three influencial parameters (in rank order based on percentage contribution) which significantly affect the MRR as well as ROC of ECDM process. The interelectrode gap has very little effect on both the responses of ECDM process.

(b) For achieving maximum MRR, the optimal level of parametric conditions are $A_3B_3C_1$, i.e., the applied voltage of 70V, electrolyte concentration of 25 per cent aqueous *KOH* and interelectrode gap of 20 mm.

(c) For achieving minimum ROC, the optimum level of parametric conditions are $A_1B_1C_2$, i.e., the applied voltage of 50V, electrolyte concentration of 15 per cent aqueous *KOH* and interelectrode gap of 30 mm.

(d) From the confirmation test results it is concluded that under optimal condition of machining, the MRR is increased to four times than that of the initial value and the improved ROC is 0.4 times than that of the initial value. The confirmation test results verify the optimal machining parameters. The improvement in the quality characteristics of ECDM process is ensured by the Taguchi method of parametric optimisation.

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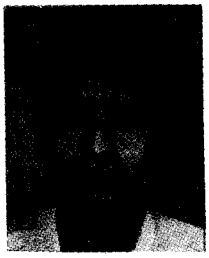

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