OPTIMIZATION OF MICRO-ELECTROCHEMICAL DISCHARGE MACHINING OF SILICON NITRIDE CERAMICS USING MOORA

S. Biswas[1], B. R. Sarkar[2], B. Doloi[3] and B. Bhattacharyya[4]

[1]Post Graduate Student, [2]Assistant Professor, [3]Associate Professor, [4]Professor,
Production Engineering Department, Jadavpur University, Kolkata- 700032, India
Email: [1]sumeet.biswas88@gmail.com, [2]sarkarbiplab_s@rediffmail.com,
[3]bdoloionline@rediffmail.com, [4]bb13@rediffmail.com

Paper received on: January 30, 2014, accepted after revision on: October 07, 2014

Abstract: Manufacturing of the better quality ceramic products with more accuracy and precision is a great challenge in the current industrial field. Electrically non-conducting materials like ceramics, composites, alumina, glass etc can be machined easily using Electrochemical Discharge Machining (ECDM) process. The performance characteristics of ECDM process e.g. material removal rate (MRR), machining depth rate (MDR), radial overcut (ROC) and heat affected zone (HAZ) are influenced by various process parameters such as applied voltage, inter-electrode gap, temperature, concentration of the electrolyte, type of electrolyte, shape, size and material of the electrode and also the nature of the power supply etc. This paper presents the optimization of m-EDMing of Silicon Nitride by utilizing Multi-Objective Optimization by Ratio Analysis (MOORA). Also, a multi choice decision analysis i.e. Analytic Hierarchy Process (AHP) is applied for optimization.

Keywords: µ-ECDM, MRR, MDR, ROC, HAZ, MOORA

1. INTRODUCTION

Electrochemical Discharge Machining (ECDM), a hybrid non-conventional machining process, is an alternative manufacturing technology for machining electrically non-conductive materials. It is the combination of electro-chemical machining (ECM) and electro-discharge machining (EDM) [1]. Here, the electrochemical reaction helps in generating positively charged gas bubbles i.e. hydrogen (H_2), which is responsible for electrical spark discharge (EDS). A high voltage D.C. power supply of 20-70V is applied between the tool (or cathode) and the auxiliary electrode (or anode). The auxiliary electrode is used in the process to complete the electrolytic cell since the workpiece material is electrically non-conducting. Some electrolyte is evaporated and gas bubbles are formed as a result of heating of the electrolyte. With increase of the voltage supply, all the bubbles i.e. hydrogen bubble and vapour bubble muster at the surroundings of smaller electrode and ultimately an insulating bubble layer is formed on it. When the threshold or critical voltage is attained, the sparking takes place in the gap from the tool to the electrolyte across an insulating bubble layer. The voltage at which the sparking starts depends on the concentration and conductivity of the electrolyte and the tool geometry. The smaller the diameter of the tool, the smaller will be the starting spark voltage [2]. Therefore, the workpiece material is removed from the localized machining zone due to the ionization at high temperature followed by melting and vapourisation. The material removal in ECDM process takes place largely due to the effects of electrical spark discharge (ESD) action.

From the beginning of the process a lot of research work has been carried out in order to study the influence of various process parameters on different machining criteria. Sarkar et al. [3] developed a mathematical model by the successful application of the response surface method (RSM) for micro-machining of silicon nitride ceramics by ECDM process. The authors verified the fitness and adequacy of the developed mathematical models and searched out the single-objective optimal condition based the developed models. Mediliyegedara et al. [4] developed a controlled strategy with the help of a pulse classification system based on an ANN. A feed-forward neural network (ANN) was trained to classify pulses with various activation functions. The trained neural networks were simulated and quantitative analysis was performed to evaluate the performance of pulse classification system. Bhondwe et al. [5] developed Finite Element Method (FEM) based model to study the temperature distribution in the workpiece and MRR with respect to change in the input parameter like electrolyte concentration, duty factor and energy partition. The present model is applied to two types of materials viz soda lime glass and alumina (Al_2O_3). Skrabalak et al. [6] presented an attempt of adapting fuzzy-logic controller for ECDM process. Fuzzy-logic and especially adaptive fuzzy-logic control system may help in reducing the number of micro-cracks and surface roughness parameter.

From the literature survey it is found few optimization techniques such as TAGUCHI, response surface methodology (RSM) etc were used in various non-conventional machining processes including ECDM process [3, 7]. But these methods are very monotonous. Therefore, this paper explores the applicability of a new MODM method, i.e. the multi-objective optimization on the basis of ratio analysis (MOORA) method to optimize different process parameters of electro-chemical discharge machining. This method is observed to be simple and computationally easy. Also Response Surface Methodology (RSM) is used for the comparison of the two optimisation processes.

2. MULTI-OBJECTIVE OPTIMIZATION ON THE BASIS OF RATIO ANALYSIS (MOORA)

Multi objective optimization, also known as multi criteria or multi attribute optimisation, is the process of optimizing two or more conflicting attributes subject to particular constraints simultaneously. The multi-objective optimization on the basis of ratio analysis (MOORA) method was first introduced by Brauers (2004). The steps followed in MOORA [8, 9] are explained in the following Fig. 1.

3. PROBLEMATIC AREAS OF MICRO-ECDM

The µ-ECDM process is influenced by various process parameters such as applied voltage, inter-electrode gap, temperature, concentration of the electrolyte, type of electrolyte, size, shape and material of the electrode and also the nature of the power supply etc. Also, there are so many problematic areas to be faced during the machining of electrically non-conducting materials by µ-ECDM process and these are shown in Fig. 2 and discussed as follows:

Operating/Handling: In micro-ECDM machines, the trend to reduce the machining time of a non conducting material, which is more useable in modern industrial field causes many problems when handling or operating the machining system.

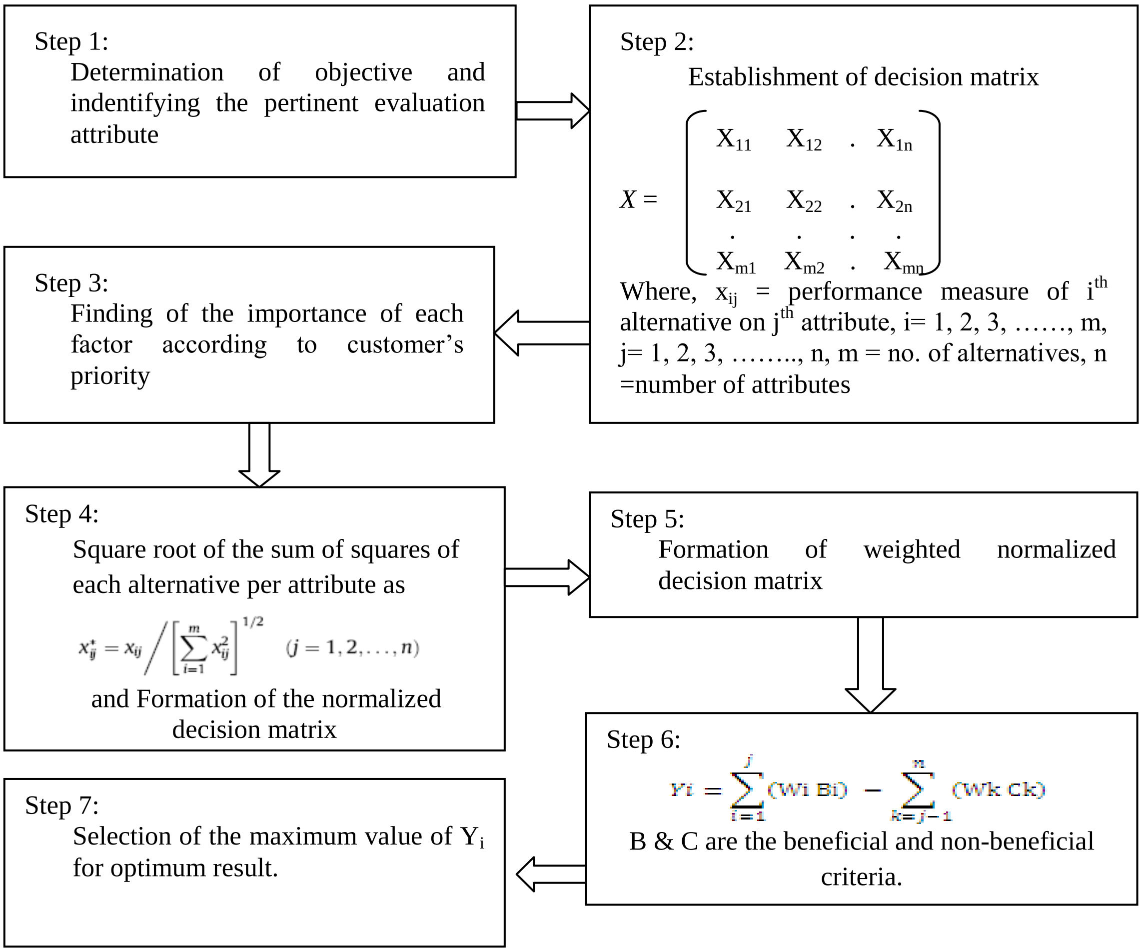

Fig. 1 Steps followed in MOORA

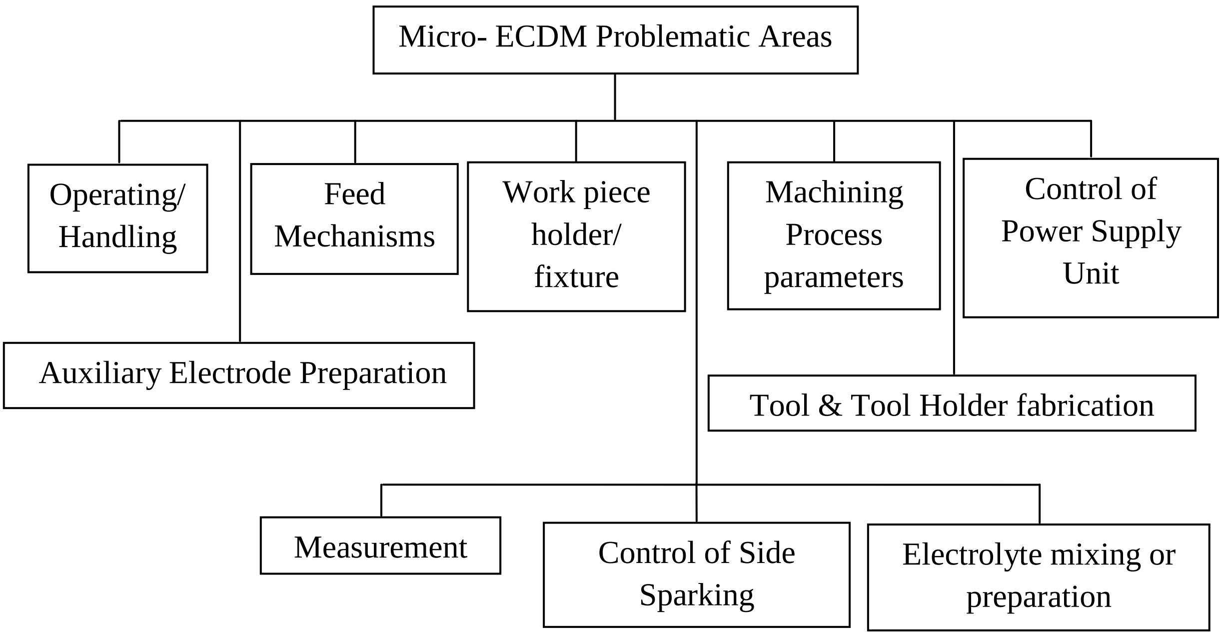

Fig. 2 Problematic areas of μ-ECDM process

When micro parts are fabricated on a micro-ECDM machine, handling the machine can also be challenging. Using micro-ECDM operations like drilling, milling, channel cutting, profile making and micro structures can be done by different techniques and devices, which are very difficult to handle.

Auxiliary Electrode Preparation: In the micro-ECDM two electrodes are used which may be of various shapes and sizes for different types of machining. The auxiliary electrode preparation is one of the most important tasks in micro-ECDM and controlling the inter-electrode gap by special devices is also a difficult task to the researchers. By using CNC regulation the inter-electrode gap can be controlled.

Feed Mechanisms: The controlling of Feed rate of micro-machining is very difficult but some of researchers used various special devices such as load cell, gravity feed mechanisms, magnetic field, digital indicator and tool vibration.

Workpiece and Fixture: In micro-ECDM, the main issues in workpiece and workpiece holder preparation related to the production of micro-holes, micro-slot cutting, micro-channel cutting and profile cutting is a very difficult task with a very high-aspect-ratio. Usually the workpiece is produced either by sintering or bonding method and the fixture is fabricated by drilling, milling, shaping etc. The accuracy of positioning of the machining zone with respect to the measuring point should be high.

Machining Process Parameters: Selection of critical process parameters for micro machining is not a very easy task. By previous research various process parameters and their ranges have been investigated and by experimental design procedure the combination of various process parameters are chosen.

Tool & Tool Holder Fabrication: The various micro-tools and the tool holder have to manufacture by using special techniques or machining process with a high aspect ratio and good accuracy of surface finish. Mainly the micro-tools are fabricated by extrusion, moulding and casting. The tool holder is manipulated by turning, drilling, milling etc.

Measurement: Measuring the dimensions or the surface quality of micro-features is also a difficult task. There are not even standardized methods of determining the surface roughness, which is one of the most important characteristics for micro-tooling. Estimation of the recast layer and heat-affected zone, which affect the properties of the machined surface, requires specialized equipment. The measurement of feature dimensions is necessary to achieve good accuracy in micro-ECDM.

Control of Power Supply Unit & Electrical Circuit: It is one of the major problems to control the DC power supply unit, which provides us the breakdown voltage and essential current flow that caused the sparking, the range of voltage and duty ratio provides this unit. It can be controlled by voltmeter and ammeter with a rectifier circuit.

Control of Side Sparking: The side sparking is one of the most problematic areas observed during μ-machining of the work material. Controlling this side sparking is not easy task. By using the heat absorbed material or insulator the side sparking may be controlled.

Electrolyte Mixing or Preparation: For micro-ECDM machining process NaOH or KOH electrolyte preparation is one of the problematic tasks. For mixture design of experiment the concentration of electrolyte maintaining is a difficult task, very carefully one has to mix the salt with water for micro-machining.

4. EXPERIMENTATION

The authors [3] have designed and developed experimental ECDM setup to study the effects of various process parameters for micro-drilling operation. The experimental setup consists of various sub-systems like: (a) Machining Chamber; (b) Job Holding Unit; (c) Tool Holding Unit; (d) Inter-Electrode Gap Control Device; (e) Gravity Controlled Job Feeding Arrangement; (f) Electrolyte Flow System Unit and (g) Pulsed DC Power Supply Unit. Schematic diagrams of the experimental setup, electrical circuitry of pulsed D.C. power supply unit and pulsed waveform used by authors [3] are shown in Fig. 3 and Fig. 4 respectively. ECDM micro-drilling was performed by the authors [3] on 20x20x5 mm Silicon Nitride (Si_3N_4) ceramics as shown in Fig. 5. Silicon Nitride ceramic material is widely used for Nitride cutting tools and turbine blades, heat exchanger, ceramic engine, welding burner and nozzle for high frequency combustion crucibles and can also be used for some special purposes such as self-lubricating and high-speed bearing etc. The experimental conditions during micro-drilling operation have been shown in the Table 1. Experimental plan based on second order rotatable central composite design [3, 10] is detailed in Table 2.

Tool of diameter less than 200 µm just created an impression on the workpiece without removing any significant amount of material during pilot experiment. Finally tool of 400 µm diameter and a tool holder made of brass were selected for the experiment as shown in Fig. 6. NaOH salt solution was used as electrolyte due to its higher electrical conductivity, which allows it to achieve a faster rate of gas bubbles' generation due to an increased rate of chemical reactions. It was found that material removal rate (MRR) increases with electrolyte concentration, it reaches its maximum value and again decreases with electrolyte concentration during drilling a hole more than 1 mm diameter [3].

Table 1 Experimental condition for micro-drilling operation on Si_3N_4

Condition Description	
Applied voltage	: 50-70 V
Electrolyte Concentration	: 10-30 wt%
Inter-electrode gap	: 20-40 mm
Duty factor	: 0.5
Frequency	: 50 Hz
Tool Polarity	: +ve
Tool electrode	: Stainless steel
Tool Diameter	: Ø400 mm
Tool shape	: Cylindrical with flat end
Auxiliary Electrode	: Copper
Electrolyte	: NaOH salt solution
Electrolyte condition	: Stagnant

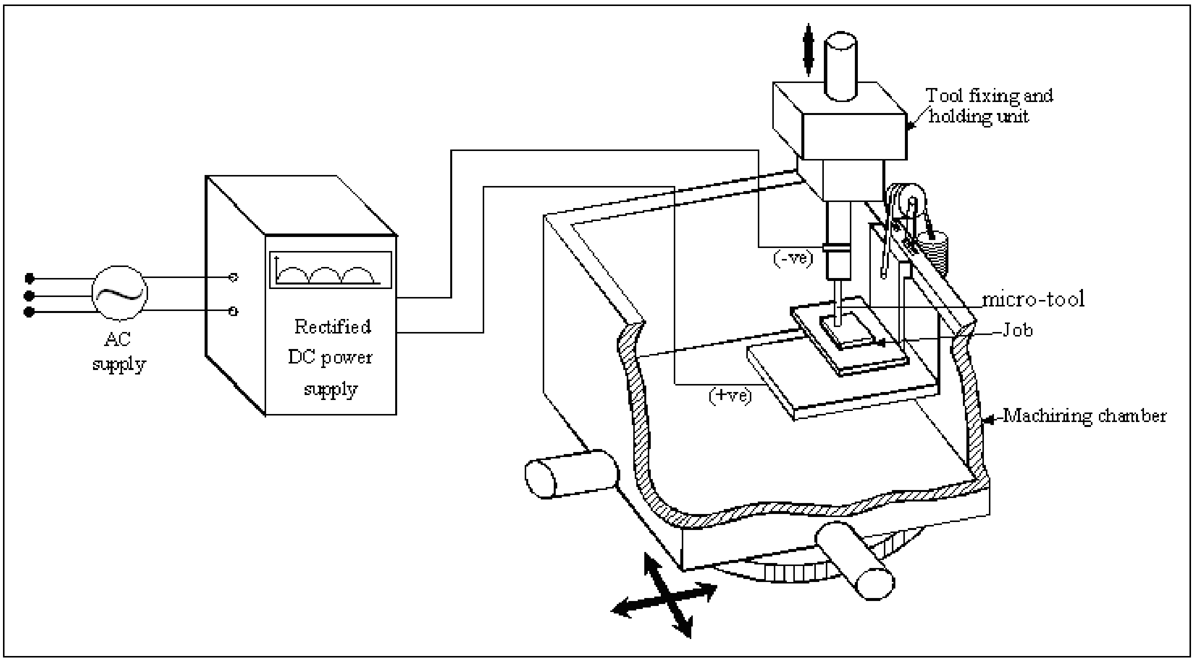

Fig. 3 Schematic diagram of ECDM setup

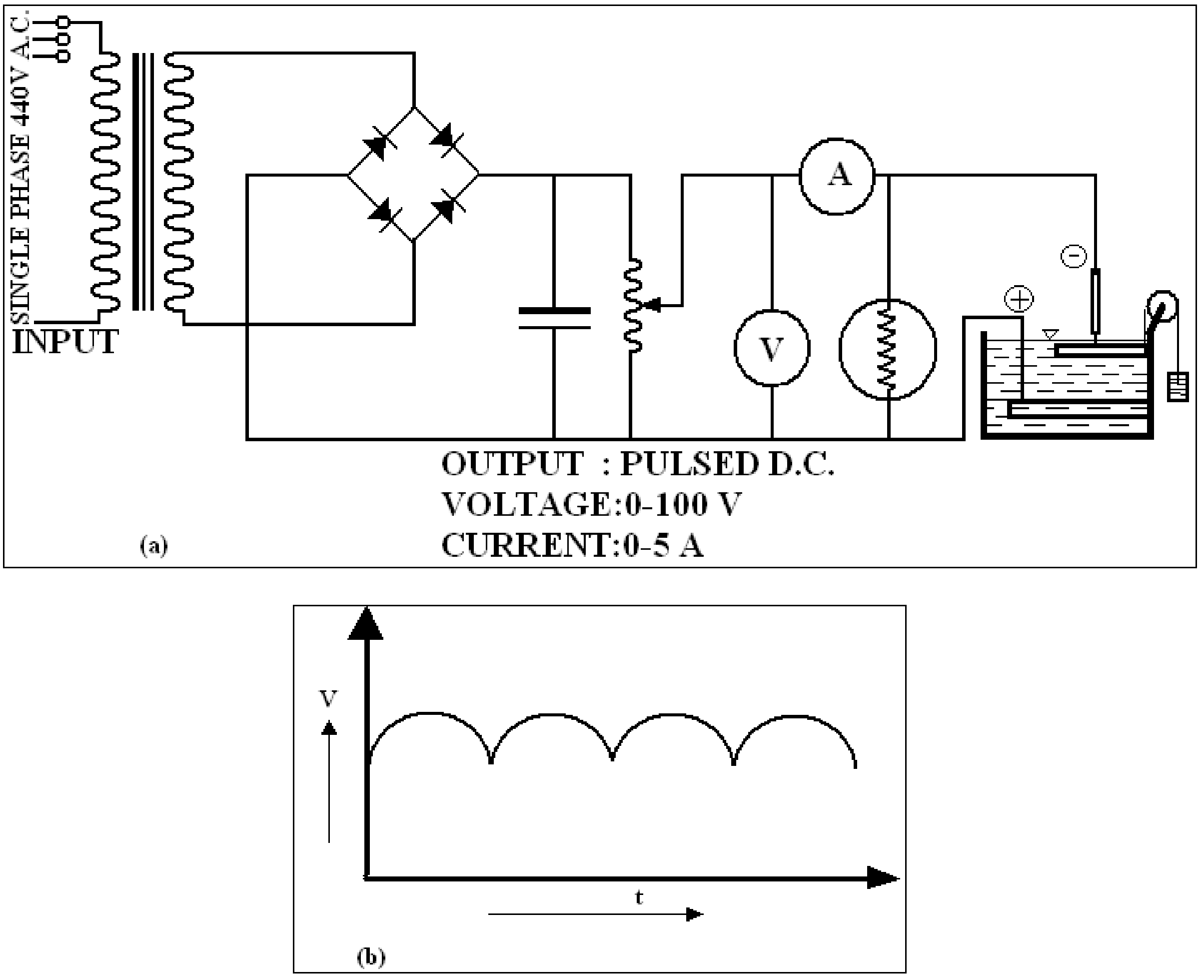

Fig. 4 (a) Pulsed D.C. power supply unit; (b) Pulsed waveform

Fig. 5 Workpiece sample of silicon nitride

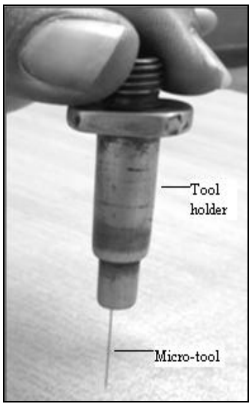

Fig. 6 Photographic view of μ-tool with tool holder

Table 2 Experimental plan and result based on second order rotatable central composite design

Expt. No.	Machining parametric combination			Experimental results			
	Voltage (V)	Concen-tration (wt %)	IEG (mm)	MRR (mg/h)	ROC (mm)	HAZ (mm)	MDR (μm/min)
1	54	14	24	0.60	0.2045	0.0987	6.244
2	66	14	24	1.03	0.2690	0.1192	8.089
3	54	26	24	0.57	0.1416	0.0736	5.370
4	66	26	24	0.73	0.2476	0.1030	7.741
5	54	14	36	0.53	0.2020	0.0981	5.122
6	66	14	36	0.80	0.1663	0.0889	7.376
7	54	26	36	0.67	0.1362	0.0610	4.089
8	66	26	36	0.69	0.2672	0.1153	7.145
9	50	20	30	0.42	0.0996	0.0543	2.848
10	70	20	30	1.20	0.3746	0.1264	8.626
11	60	10	30	0.55	0.2432	0.1013	3.878
12	60	30	30	0.40	0.1899	0.0983	4.641
13	60	20	20	0.67	0.1866	0.0923	7.256
14	60	20	40	0.53	0.1826	0.0623	3.337
15	60	20	30	0.40	0.1836	0.0673	5.489
16	60	20	30	0.93	0.2379	0.0764	8.004
17	60	20	30	0.53	0.1444	0.0998	6.778
18	60	20	30	0.53	0.1308	0.0805	7.193
19	60	20	30	0.67	0.1089	0.0746	5.067
20	60	20	30	0.57	0.1590	0.0723	7.189
			SSQ	0.832965	0.1633678	9.2938	793.702374
			SQRT	0.9126692	0.4041878	3.0485734	28.1727234

During pilot experimentation, it was observed that gas bubbles' formation occurs in the range of 6-12 V for varying electrolyte concentration and the spark generates in the range of 20-30 V. The micro-cracks on Si_3N_4 workpiece occur at 75 V for 30% NaOH salt solution. The auxiliary electrode was larger than the cathode tool. The desired inter-electrode gap was maintained by means of lowering or lifting the auxiliary electrode to the proper position using a screw-nut mechanism. The tool can also be moved up and down by a rotating lead screw to adjust the inter-electrode gap. The feed motion was applied to the workpiece by a gravity feeding unit with an adjustable counterweight. Rectified pulsed D.C power supply was selected. The voltage was applied by controlling the variac. The experiments were carried out using stagnant electrolyte and a stationary tool because of flowing of electrolyte removes the gas bubbles generated during machining operation resulting in weak sparking and low material removal rate. The level of electrolyte changed due to boiling and evaporation. It was adjusted by means of regulating the flow of electrolyte in the machining chamber.

To explore the multi-parametric combinations for the ECDM process on non-conducting ceramics, experiments were carried out according to a second order rotatable central composite design (CCD) based on response surface methodology (RSM). The material removal rate (MRR), machining depth rate (MDR), radial overcut (ROC) and thickness of heat affected zone (HAZ) are obtained through a series of experiments according to the experimental plan as shown in Table 2. Depth, diameter and HAZ of the machined holes were measured using Olympus measuring microscope (LC 0.1 mm) at the magnification of 5X and 10X respectively.

5. OPTIMAL PARAMETRIC COMBINATION USING MOORA

Material removal rate (MRR), radial overcut (ROC), heat affected zone (HAZ) and machining depth rate (MDR) have been chosen as factors and inter-electrode gap, applied voltage, electrolyte concentration as alternative during micro-machining of Si_3N_4 by ECDM process. Another technique used in this paper for optimisation is Analytic Hierarchy Process (AHP) [11, 12] for determining the weights from pair-wise comparison matrix. The weighted-normalized decision matrix is formed using the weights. In this paper ROC, HAZ, MRR and MDR are represented as F_1, F_2, F_3 and F_4 respectively. MRR & MDR are considered as beneficial attribute (i.e. higher values are desirable) whereas ROC & HAZ are considered as non beneficial attribute (i.e. lower values are desirable). The decision matrix for the optimal parametric combination selection problem is shown in Table 2. The relative importance (weight) of these attributes is calculated using AHP method and shown in Table 3. The values for F_1, F_2, F_3 and F_4 are assigned in a 1 to 5 scale. These values are chosen based on some previous research works [1-3, 7, 10]. Applying step 4 the normalized decision matrix is obtained and shown in Table 4. Then the weighted normalised matrix and also the assessment values (y_i) of the considered alternatives with respect to the selection criteria are computed based on these criteria weights using step 5 and step 6. All the assessment values as shown in Table 5 are positive in nature. The optimal parametric combination was chosen on the basis of ranking (step 7), which was apportioned based on the assigned values. From the weighted normalized decision matrix Table 5 it can be said the optimum condition is found to be most significant and the best condition is obtained as 70V/ 20wt%/ 30 mm. The optimal values of material removal rate, machining depth rate, radial overcut and average heat affected zone are measured as 1.20 mg/h, 8.626 mm/min, 0.3746 mm and 0.1264 mm respectively. The optimal condition corroborates the experimental results obtained by authors [3, 10].

Table 3 Pair-wise Comparison Matrix

Expt. No.	F_1	F_2	F_3	F_4
1	0.2240	0.2441	0.1968	6.24
2	0.2947	0.2949	0.3378	8.08
3	0.1551	0.1820	0.1869	5.37
4	0.2712	0.2548	0.2394	7.74
5	0.2213	0.2427	0.1738	5.12
6	0.1822	0.2199	0.2624	7.37
7	0.1492	0.1509	0.2197	4.08
8	0.2927	0.2852	0.2263	7.14
9	0.1091	0.1343	0.1377	2.84
10	0.4104	0.3127	0.3936	8.62
11	0.2664	0.2506	0.1804	3.87
12	0.2080	0.2432	0.1312	4.64
13	0.2044	0.2283	0.2197	7.25
14	0.2000	0.1541	0.1738	3.33
15	0.2011	0.1665	0.1312	5.48
16	0.2606	0.1890	0.3050	8.00
17	0.1582	0.2469	0.1738	6.77
18	0.1433	0.1991	0.1738	7.19
19	0.1193	0.1845	0.2197	5.06
20	0.1742	0.1788	0.1869	7.18
Wt.	0.4918	0.1639	0.0983	0.24

Table 4 Normalised Decision Matrix

	F_1	F_2	F_3	F_4	**GM**	**RP**
F_1	1	3	5	2	2.3403	0.4918
F_2	1/3	1	5/3	2/3	0.7801	0.1639
F_3	1/5	3/5	1	2/5	0.4680	0.0983
F_4	1/2	3/2	5/2	1	1.1701	0.2459
				SUM	4.7587	

Table 5 Weighted Normalized Decision Matrix

Expt. No.	F_1	F_2	F_3	F_4	y_i	**Rank**
1	0.1101974	0.0400317	0.01935870	1.535410215	1.4045398	11
2	0.1449541	0.0483463	0.03323244	1.989098851	1.8290310	3
3	0.0763030	0.0298514	0.01839077	1.320492129	1.2327286	13
4	0.1334224	0.0417757	0.02355309	1.903525060	1.7518800	4
5	0.1088503	0.0397883	0.01710019	1.259508507	1.1279701	15
6	0.0896129	0.0360569	0.02581160	1.813770939	1.7139128	5
7	0.0733931	0.0247410	0.02161722	1.005492051	0.9289752	17
8	0.1439841	0.0467645	0.02226251	1.756967647	1.5884816	9
9	0.0536707	0.0220235	0.01355109	0.700328042	0.6381849	20
10	**0.2018580**	**0.0512665**	**0.03871741**	**2.121148064**	**1.9067410**	**1**
11	0.1310514	0.0410862	0.01774548	0.953606793	0.7992146	18
12	0.1023300	0.0398694	0.01290580	1.141229790	1.0119361	16
13	0.1005518	0.0374359	0.02161722	1.784262735	1.6678923	8
14	0.0983963	0.0252682	0.01710019	0.820573973	0.7140096	19
15	0.0989352	0.0272962	0.01290580	1.349754431	1.2364289	12
16	0.1281954	0.0309870	0.03000599	1.968197207	1.8390207	2
17	0.0778118	0.0404778	0.01710019	1.666721723	1.5655323	10
18	0.0704832	0.0326500	0.01710019	1.768770928	1.6827379	6
19	0.0586822	0.0302570	0.02161722	1.245983914	1.1786620	14
20	0.0856792	0.0293241	0.01839077	1.767787321	1.6711748	7

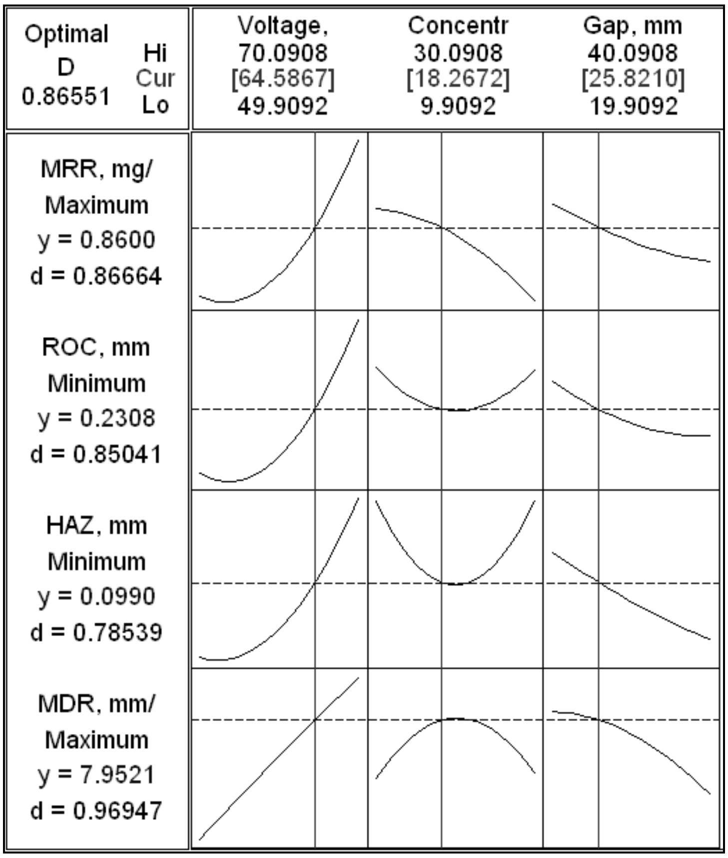

Fig. 7 RSM based result showing optimal parametric combination with expected outcome

Also, another optimisation technique has been used for the comparison of the outcomes. The RSM process gives the optimal parametric combination of applied voltage of 64.58 V, electrolytic concentration of 18.26wt% and IEG of 25.82 mm where the expected results are MRR = 0.86 mg/hr, ROC = 0.2308 mm, HAZ = 0.0990 mm and MDR = 7.9521 µm/min etc. The following Fig. 7 shows the RSM result for optimum parametric combination with their expected results. Comparing MOORA and RSM it is clear that the parametric combination given by MOORA has an outcome with maximum MRR and moderate ROC and HAZ with high MDR and those are experimentally obtained by the authors [3, 10] whereas RSM gives the parametric combination with the lower expected results of MRR, ROC, HAZ and MDR and it is a matter of fact that the outcomes from the RSM process are expectations only. According to this theory the results may be the exact or vice versa. So MOORA is more favourable optimisation technique that can be used for this type of problem.

6. CONCLUSIONS

MOORA method can be used effectively for parametric optimization of µ-ECDM of Silicon Nitride ceramics. This method is computationally very simple, easily comprehendible and robust, which can simultaneously consider any number of quantitative and qualitative selection attributes, while offering a more objective and logical selection approach. The optimal condition for maximum MRR & MDR and minimum ROC & HAZ is obtained at 70V/20wt%/30mm. The outcome of present work will be beneficial to manufacturing industries during micro-machining of electrically non-conducting materials by ECDM process.

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