Modelling and analysis on performance of ECDM process for the fabrication of μ-channels on glass through response surface methodology

Bijan Mallick[1], Biplab Ranjan Sarkar[*2], Biswanath Doloi[3] & Bijoy Bhattacharyya[4]

Production Engineering Department, Jadavpur University, Kolkata, W.B

ABSTRACT

Keywords:
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The process electro-chemical discharge micro-machining can be utilized to produce micro-channels, micro-profiles, blind holes and miniature parts with ceramic, composite, quartz and glass. This research paper enlightens the development of micro-ECDM system and the influences of process variables like duty ratio (%), pulse frequency (Hz), electrolyte concentration (wt%) and applied voltage (V) on material removal rate (MRR), overcut (OC), heat affected zone (HAZ) and surface roughness (R_a) to improve the machining efficiency as well as better quality of surface integrity during micro-channel cutting on glass using spring feed mechanism in ECDM process. The mathematical models of above machining criteria are established with help of response surface methodology (RSM) and their adequacies have been justified through Analysis of Variance (ANOVA) test. This research article also emphasises on the single and multi-objective optimization to find out suitable parametric condition for micro-channel cutting on glass. MRR is found maximum at 55V/30wt%NaOH/40%/200Hz and better surface quality of μ-channel is achieved with higher machining depth at 35V/30wt%NaOH/60%/660Hz. Further, this research paper includes a qualitative analysis of micro-channels based on SEM and XRD analyses to identify the phase change, micro-cracks and presence of uncut silica debris in the channels.

1. Introduction

Electro-chemical discharge machining (ECDM) process, an advanced hybrid unconventional machining process, is involved in the field of micro-machining of non-conducting materials with electrically low conductivity. This process combines mechanisms of both non-conventional ECM and EDM processes, where ECM is responsible for the bubble generation by electrochemical reactions in the electrolyte medium whereas EDM is responsible for spark discharges at the tool-electrolyte interface across the bubbles and material is removed due to melting and vapourisation [1-3]. The ECM process is followed by EDM process in ECDM process.

*Corresponding author,
E-mail: sarkarbiplab_s@rediffmail.com
(Biplab Ranjan Sarkar)

The authors explained the mechanism of spark generation of this process. But the mechanism of the process is not lucid to all and effected by different factors. That is why the researchers are still attempting several efforts to overcome the problems associated with this process. Elhami and Razfar [4, 5] showed the effects of ultrasonic vibration on removal of workpiece and tool materials and also on the gas film thickness. Singh et al. [6] used pressurized feeding system with abrasive coated tool to control the working gap for creating stable gas film. Tang et al. [7] used diamond coated side insulated tool to reduce the effect of side wall discharge for improving the surface texture. The applied voltage had greater influence on machining depth as well as machining rate in compared to inter-electrode gap [8]. Han et al. [9] fabricated micro-grooves with high aspect ratio by using ECDM micro-milling process. The machined surface became smoother when the electrolyte concentration was low under the magnetic field during ECDM milling of glass [10]. Saranya et al. [11] carried out a systematic study on the electrical characteristics during micro-channel cutting on glass with a dynamic cylindrical tool. Baoyang et al. [12] improved the consistency of sparking using tapered tool electrodes. Mallick et al. [13] optimized the multi-criteria to find out the optimal parametric condition for achieving better machining depth. Cao et al. [14] used polycrystalline diamond (PCD tools for improvement of the surface quality. Cheng et al. [15] improved the machining efficiency and accuracy of ECDM by magnetic field. The suitable power circuit configuration for micro-machining of electrically non-conducting materials by ECDM process was designed by Sarkar et al. [16]. The accuracy of μ-holes on ceramics was influenced applied voltage, electrolyte concentration, flat front-flat side wall tool and pulse voltage [17, 18]. The influences of different parameters on machining criteria during μ-drilling on Si_3N_4 and SiC ceramics were analysed though developed empirical models [19, 20]. ANN models were used for the validations of single/multi-objective optimization during electrochemical discharge drilling of SiC reinforced epoxy composites [21]. Preliminary investigations were carried out to analyse the effects of tool rotational speed and tool static force on drilling performance on borosilicate glass with use of a grinding-aided electrochemical discharge machine (G-ECDM) set-up [22].

But, till date no research work was published about the influence of pulse frequency, duty ratio and applied voltage during micro-channelling on glass by ECDM process using a spring-feed mechanism. Therefore, this research paper enlightens the development of ECDM set-up for experimentation and the effects of process parameters like duty ratio (%), pulse frequency (Hz), electrolyte concentrations (wt%) and applied voltage (V) on material removal rate (MRR), heat affected zone (HAZ), overcut (OC) and surface roughness (R_a) to improve the machining efficiency and better quality of surface integrity during μ-channel cutting on glass using a spring feed mechanism in micro-ECDM process. Not only that this research paper also includes the empirical models for MRR, OC, HAZ and surface roughness established through response surface methodology (RSM). The analysis of variances (ANOVA) test has been done to validate those models during micro-channel cutting on glass. Single and multi-responses have been optimized to search out the suitable parametric condition to cut micro-channel with better surface quality as well as to improve the machining rate. Further, this research paper includes a qualitative analysis of micro-channels based on SEM and XRD reports to identify the phase change, micro-cracks and presence of uncut silica debris in the μ-channels.

2. Development of Micro-ECDM Set-Up

Knowing the advantages and disadvantages of feed mechanism of micro-tool and tool holder, gravity feed control of the work piece of micro-ECDM set-up and the aim of present research work and the knowledge base through the previous research works on electrochemical discharge machining (ECDM) a new set-up is indigenously designed and fabricated for better accuracy, modified feeding arrangement and also for channel making with minimum error. The experimental setup comprises of the sub-systems and mechanisms: (i) machining chamber, (ii) dovetailed slider and workpiece guide mechanism, (iii) spring feed mechanism, (iv) tool guide mechanism, (v) electrolyte reserver unit, (vi) electrical power supply unit.

The rectangular box shaped machining chamber is fabricated with acrylic sheet due to its transparency, shock resistance property and chemically non-reactive with the electrolytic solution. The job sample is kept fixed tightly on a plate, which itself rests on four rods positioned at four corners of the plate for obtaining required machining performance. These rods guide four springs so that the job holding plate can move up and down along the axis of rods i.e. only vertical movement can be applied to both job holding plat and job sample. Thus the feeding to job sample is given due to extension of these springs and it is referred as spring-feed mechanism. For the horizontal movement of the job fixing plate as well as job sample a dovetailed slider is used. In order to generate different profiles of micro-channels with help of present experimental set-up a cam-follower mechanism is used. A template, which has a curved profile on its outer periphery acts as a cam, is made and fitted with the tool holding unit so that the tool will be in direct contact with the template and can travel along the profile of template with help of a guide pin, which serves the purpose of a follower. A lever/ handle is used to revolve the tool holding unit along with micro-tool with it and in accordance with requirements, the position of micro-tool is synchronized by a screw-nut mechanism, which is used to fix the tool-holding unit cover plate. This mechanism helps in upward

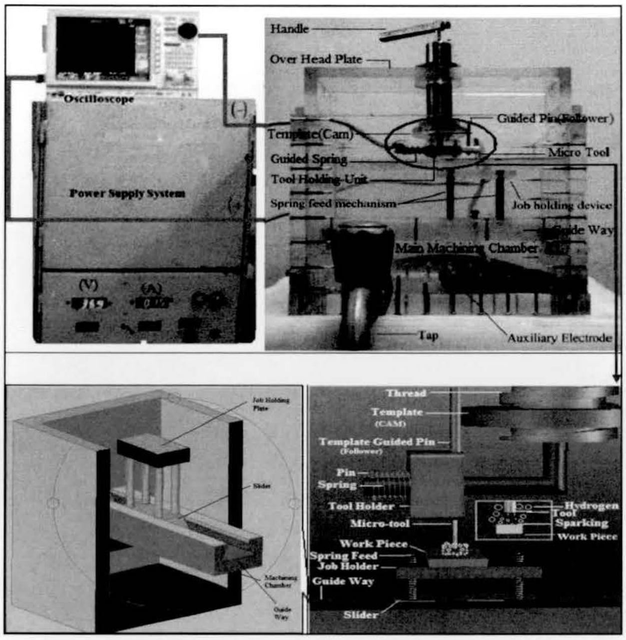


Fig. 1. Photographic and schematic views of Micro-ECDM system.

and downward displacement of the tool holding unit. The Fig. 1 represents the photographic and schematic views of experimental set-up.

3. Experimental Plan

The experiments were conducted in alkaline NaOH electrolyte solution with a cylindrical stainless steel μ-tool of diameter 250μm. The process variables i.e. applied voltage, electrolyte concentration, duty ratio and pulse frequency were varied as 35-55 V; 20-30wt%; 40-60%, and 200-1000 Hz respectively. Here, the experiments were performed at different voltage levels of pulsed DC power supply. Silica glass was chosen as work piece material to cut micro-channels. Always new identical μ-tool electrode was used in every single experiment to nullify the errors caused due to the tool wear during micro-ECDM process. The inter-electrode gap was kept fixed as 40 mm while the experiments were conducted according to face centred design (FCD) of response surface methodology (RSM). All experiments were conducted in a stagnant electrolyte since flow of electrolyte moves away the bubbles from the machining zone and then there will be no spark discharge, ultimately no material removal.

The second order polynomial response surface empirical expression [23], which correlates various process variables with different machining responses, can be written as below:

$$Y_u = b_0 + \sum_{i=1}^{n} b_i X_{iu} + \sum_{i=1}^{n} b_{ii} X_{iu}^2 + \sum_{i<j} b_{ij} X_{iu} X_{ju} + \varepsilon \qquad \text{Eq. (1)}$$

Where,

Y_u = the machining characteristics, e.g. MRR, OC, HAZ and R_a etc,

X_{iu} = the coded values of i^{th} process variables for u^{th} experiment,

ε = the error,

n = number of process variables and

b_i, b_{ii}, b_{ij} = regression coefficients.

For this experimentation the upper and lower levels were coded as +1 and −1 respectively for each process variable. Here, X_1 = Voltage, X_2 = Electrolyte concentration, X_3 = duty ratio and X_4 = pulse frequency.

Machining rate in terms of material removal rate (MRR) was determined by mass difference of work piece before and after machining with aid of weighing balance (LC 0.01 mg) and the overcut of micro-channels was estimated by deducting the tool diameter from the width-of-cut of μ-channels. The Leica measuring microscope was used to measure HAZ area of micro-channels and the surface roughness (R_a) of micro-channels was quantified by using Mitutoyo Surface Roughness Tester (model: 178-561-02A Surftest SJ-210).

4. Results and Discussion

The data obtained from the experimentations were employed as input to MINITAB 16 software for establishing the empirical models and preparing the graphs to analysis the effects of various process variables on machining responses for achieving optimum MRR, OC, HAZ area and R_a during electrochemical discharge micro-channel cutting on glass. Each experiment was conducted three times at every parametric combination as shown in Table 1 and the average of three experimental results were used for analyses and optimisation. Table 1 also represents those experimental results.

4.1. Empirical models for MRR, OC, HAZ and R_a

The empirical expressions were developed for correlating the μ-ECDM process variables with different machining characteristics during micro-channel cutting on glass. The empirical models on MRR, OC, HAZ and R_a of micro-ECDM have been expressed as below.

$$Yu\ (MRR) = 65.318+5.463X_1+14.380X_2+5.848X_3 -13.486X_4+15.32X_1^2-5.30X_2^2 -1.15X_3^2+8.09X_4^2+0.745X_1X_2- 1.113X_1X_3 - 1.128X_1X_4 - 1.128X_2X_3 + 0.470X_2X_4 + 6.473X_3X_4 \ \text{......... Eq.(2)}$$

Table 1
Experimental result at different parametric conditions.

SL No.	Voltage (V)	Electrolyte con. (wt%)	Duty ratio (%)	Pulse frequency(Hz)	MRR (mg/hr)	OC (µm)	HAZ (µm^2)x10^3	Surface Roughness Ra(µm)
1	35	20	40	200	72.93	212.856	264.12	1.2387
2	55	20	40	200	88.65	265.234	384.23	1.7980
3	35	30	40	200	102.48	186.430	336.80	1.4873
4	55	30	40	200	122.42	288.240	580.24	2.3881
5	35	20	60	200	77.56	254.650	271.34	1.2700
6	55	20	60	200	86.87	294.432	296.70	1.3200
7	35	30	60	200	102.56	155.240	323.22	1.4077
8	55	30	60	200	112.24	309.447	532.20	1.7560
9	35	20	40	1000	35.55	108.365	259.78	1.3100
10	55	20	40	1000	46.31	202.234	392.24	2.0413
11	35	30	40	1000	68.45	106.356	279.11	1.2540
12	55	30	40	1000	76.56	299.586	528.43	2.2890
13	35	20	60	1000	64.34	104.856	271.23	1.3978
14	55	20	60	1000	68.22	264.494	333.80	1.6948
15	35	30	60	1000	88.38	104.874	265.11	1.2050
16	55	30	60	1000	102.24	309.584	412.30	1.6952
17	35	25	50	600	77.47	132.299	218.90	1.2060
18	55	25	50	600	84.54	302.867	369.30	1.8460
19	45	20	50	600	48.42	273.223	288.66	1.6114
20	45	30	50	600	72.36	264.494	380.12	1.7240
21	45	25	40	600	56.44	210.265	248.00	1.6003
22	45	25	60	600	72.64	208.000	201.60	1.3931
23	45	25	50	200	87.32	278.376	342.24	1.9686
24	45	25	50	1000	60.24	243.243	334.00	2.0830
25	45	25	50	600	66.18	254.212	267.34	1.6850
26	45	25	50	600	66.12	257.278	268.12	1.7045
27	45	25	50	600	65.82	252.278	269.15	1.7070
28	45	25	50	600	66.15	258.320	267.12	1.7023
29	45	25	50	600	62.24	256.342	264.98	1.7120
30	45	25	50	600	64.24	256.876	265.71	1.6980
31	45	25	50	600	64.26	258.387	266.98	1.7021

$$Y_u(OC) = 252.53 + 65.01X_1 + 2.443\ X_2 + 7.00\ X_3 - 27.85\ X_4 - 30.61\ X_1^2 + 20.67\ X_2^2 - 39.06\ X_3^2 + 12.62\ X_4^2 + 19.27X_1X_2 + 7.32\ X_1X_3 + 18.95\ X_1X_4 - 8.20\ X_2X_3 + 14.27\ X_2X_4 + 0.39X_3\ X_4 \quad \text{.....Eq. (3)}$$

$$Y_u(HAZ) = 271.16+74.44X_1+48.64X_2-20.30X_3-14.17X_4+18.15X_1^2+58.44X_2^2-51.15X_3^2 + 62.17X_4^2 + 31.78X_1\ X_2\ -18.83X_1X_3 - 0.40\ X_1\ X_4 - 4.03\ X2\ X3\ -20.51\ X2\ X4 - 2.20\ X_3\ X_4 \quad \text{..... Eq. (4)}$$

$$Y_u(R_a) = 1.70341 + 0.28066X_1 + 0.08468X_2 - 0.12595X_3 - 0.01865X_4 - 0.1796\ X1^2 - 0.0379X2^2 - 0.2089X3^2 + 0.3202X_4^2 + 0.07104X_1X_2 - 0.12756X_1X_3 + 0.04344\ X_1\ X_4 - 0.04057\ X_2\ X_3 - 0.08832\ X_2X_4 + 0.01606\ X_3X_4 \quad \text{..... Eq. (5)}$$

Response surface regression analysis for MRR, OC, HAZ and R_a was performed using coded units of process variables. From the analysis it is cleared that the linear, square and interaction effects of voltage applied, electrolyte concentration, pulse frequency and duty ratio are significantly influencing the variation of MRR, OC, HAZ and Ra because of each p-value are found to be smaller than 0.05. The 'S' values of the models for MRR, OC, HAZ and R_a are determined as 2.36221, 13.1440, 12.8145 and 0.0302176 respectively in order to examine the fitness of empirical models. The values of R^2 and adj-R^2 for MRR, OC, HAZ and R_a are calculated as 99.21% & 98.51%, 97.77% & 95.82%, 98.94% & 98.01% and 99.48% & 99.02% respectively and these terms reveal the non-presence of insignificant terms in those empirical models. Therefore, the data of every machining characteristic are well adjusted in the above models and can be utilized for prediction too.

In the ANOVA test, 'F-ratio values [23] were used to justify the adequacy of developed models. Table 2 shows the analysis of variance (ANOVA) test results for all machining characteristics. The standard F-ratio values (2.32260) are found to be greater than the calculated F-ratio values of 'lack-of-fit' for 10 DOF or 4.6 for 5 DOF. Therefore, it is inferred that the second order non-linear regression models are adequate at 95% confidence level for 10 DOF or 5 DOF to present the relationship between the micro-machining performances and machining variables of µ-ECDM process. Estimated regression coefficients and analysis of variance for those machining criteria suggest that these models adequately fit the experimental data.

4.2. Parametric analysis of micro-ECDM characteristics

The influences of the process variables e.g. applied voltage, electrolyte concentration, duty ratio and pulse frequency on machining characteristics i.e. MRR, OC, HAZ and R_a at the time of micro-channeling on glass have been illustrated based upon the empirical expressions as developed using RSM.

(i). Effects of process variables on Material Removal Rate (MRR)

From the RSM based empirical model the parametric influences of applied voltage, electrolyte concentration, duty ratio and pulse frequency on machining rate i.e. material removal rate are shown in Figs. 2 (i) and (ii). These figures reveal that MRR reduces with increase of pulse frequency but increases with the raise of voltage applied, electrolyte concentration and duty ratio. Electrolyte concentration, pulse on-time, applied voltage and its frequency influence the bubbles generation, which ultimately controls the spark discharge and thereby MRR changes. Fig. 2 shows that material removal rate becomes higher at high voltage and concentration because when the applied voltage increases, the rate of discharge boosts up and also the conductivity is increased

Table 2

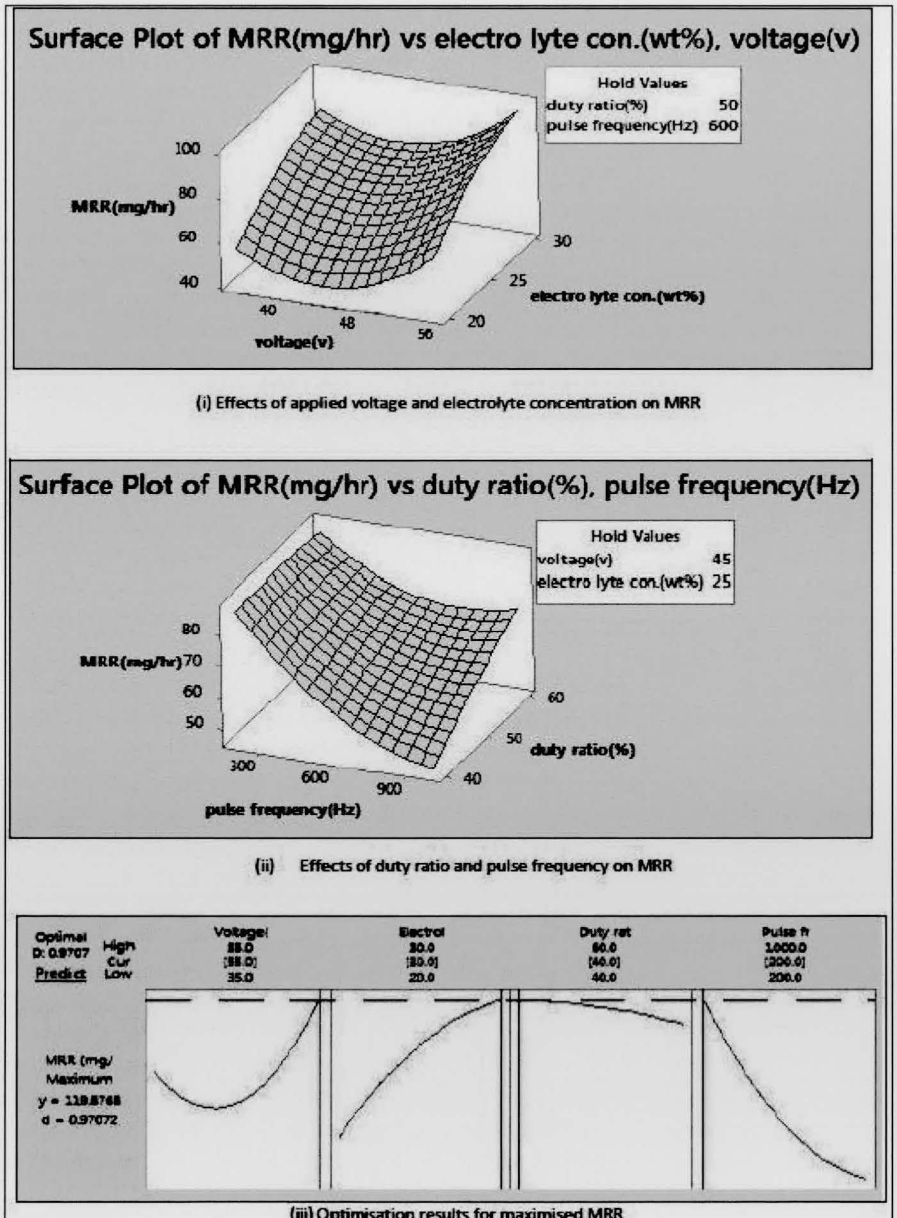
Analysis of Variance (ANOVA) test results for MRR, OC, HAZ and R_a.

Source	DOF	SS				MSS				F-value				P-value			
		MRR	OC	HAZ	R_a	MRR	OC	HAZ	R_a	MRR	OC	HAZ	R_a	MRR	OC	HAZ	R_a
Regression	14	11146.9	121351	245284	2.78745	796.21	8667.9	17520.3	0.19910	142.69	50.17	106.69	218.05	0.000	0.000	0.000	0.000
Linear	4	8148.3	91026	153341	1.83876	2037.07	22756.5	38335.4	0.45969	365.06	131.72	233.45	503.44	0.000	0.00	0.000	0.000
Square	4	2255.4	13445	63045	0.42215	563.86	3361.2	15761.2	0.10554	101.05	19.46	95.98	115.58	0.000	0.000	0.000	0.000
Interaction	6	743.2	16880	28898	0.52654	123.86	2813.3	4816.3	0.08776	22.20	16.28	29.33	96.11	0.000	0.000	0.000	0.000
Lack-of-Fit	10	75.9	2734	2616	0.01417	7.59	273.4	261.6	0.00142	2.35	2.25	2.18	1.55	0.074	0.000	0.000	0.001
Pure Error	6	13.4	30	12	0.00043	2.23	5	2	0.00007								
Total	30																

for increment of electrolyte concentration and the spark discharges with higher intensity take place. Further, MRR enhances with extend of duration of pulse on-time, which is changed with duty ratio. But with increase of pulse frequency MRR becomes low since the discharge duration widens with fall in frequency, even though the total time for that voltage remains unaltered. Fig. 2 exhibits that if the duty ratio and pulse frequency are fixed at 50%z and 600H respectively, MRR becomes higher at 50V/30wt%. Again if the voltage and electrolyte concentration are maintained at the level of 40 V and 25wt%, MRR enhances with increase of duty ratio up to 60% and reduces with raise of pulse frequency and becomes higher at 45V/25wt%/60%/200Hz. Fig. 2(iii) shows the graphical representation of single optimization for maximum MRR based on Eq. (2). By using MINITAB 16 software maximum MRR has been obtained as 119.8768mg/hr at the parametric combination of 55V/30wt%NaOH/40%/200Hz for optimization of the electrochemical discharge micro-channeling on glass.

(ii). Effects of process variables on Overcut (OC)

For achieving higher accuracy of micro-channels minimisation of overcut is highly needed during electrochemical discharge micro-channel cutting operation. Therefore, the effects of ECDM process variables e.g. voltage applied, duty factor, pulse frequency and electrolyte concentration on overcut during micro-channel cutting on 1mm thick glass substrate has been explored based on the empirical model by using RSM based approach. Figs. 3 (i) and (ii) represent the influences of above process variables on overcut using NaOH as electrolyte. Generally, due to raise of both voltage applied and concentration the rate of sparking is promoted and subsequently it bumps up both MRR and width-of-cut owing to sidewall sparking from the tool electrode. Whereas in the Fig. 3 it is evident that with enhancement of pulse frequency overcut reduces and increases with increment of duty ratio. The feasible cause may be that on the tool's side surface the current intensity rises and the discharge gets stronger at that region on account of more number of bubble generation. As seen in Fig. 3 if the pulse frequency and duty ratio are set at 600Hz and 50%

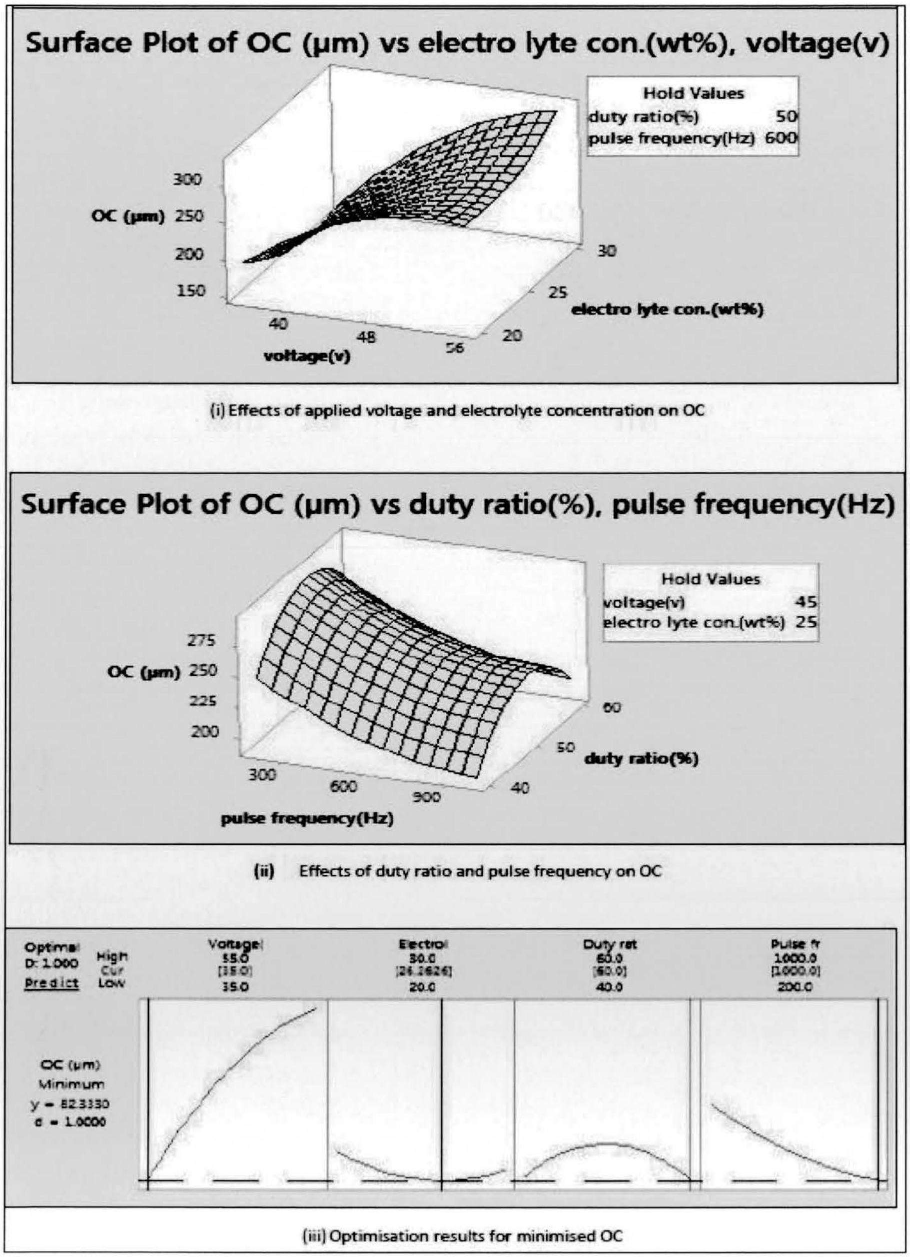


(i) Effects of applied voltage and electrolyte concentration on MRR

(ii) Effects of duty ratio and pulse frequency on MRR

(iii) Optimisation results for maximised MRR

Fig. 2. Effects of process parameters on MRR.



(i) Effects of applied voltage and electrolyte concentration on OC

(ii) Effects of duty ratio and pulse frequency on OC

(iii) Optimisation results for minimised OC

Fig. 3. Effects of process parameters on OC.

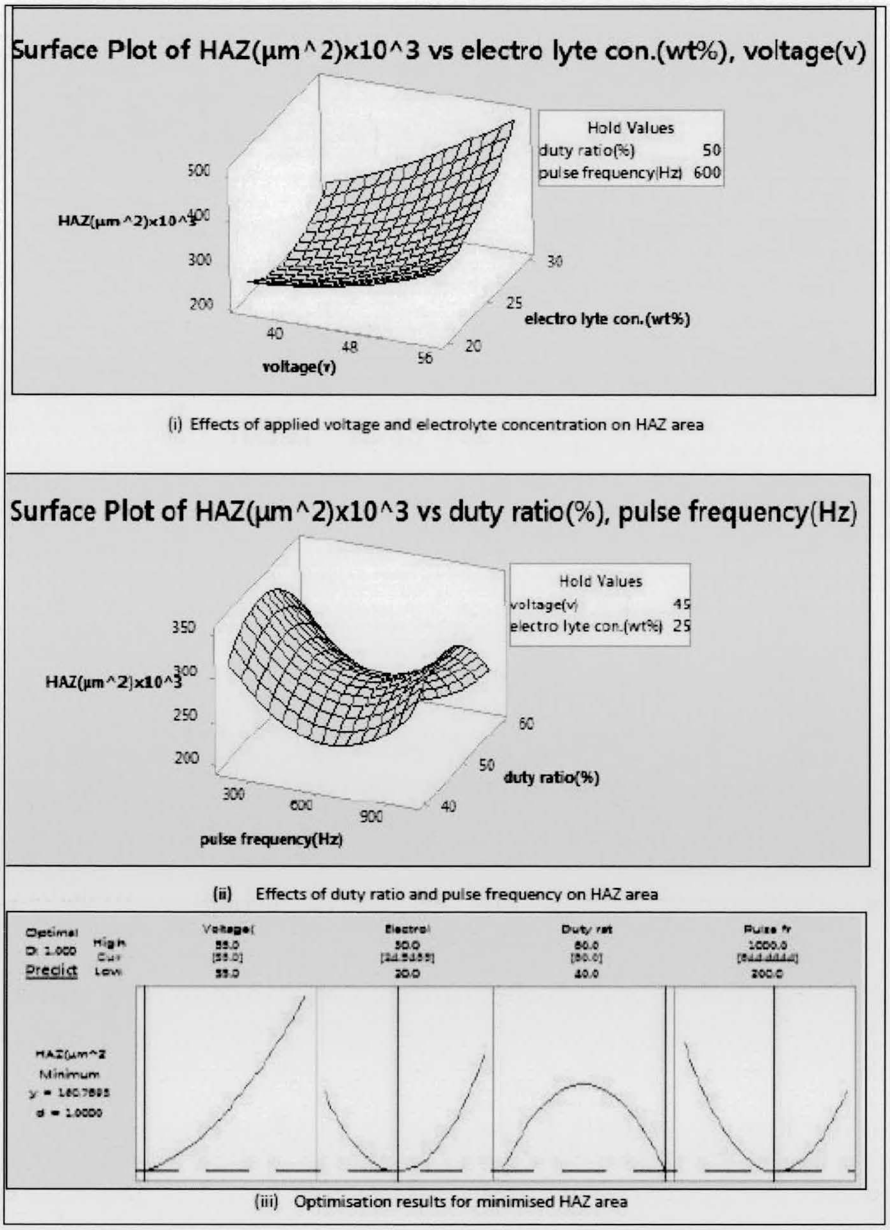
value is given here as 1 for linear desirability function (d).

(iii). Effects of process variables on Heat Affected Zone

A bulky amount of heat is evolved in μ-ECDM process for the period of the micro-channelling on glass. A segment of this heat is engrossed to the electrolyte due to convection, some is spread to atmosphere by radiation and the leftover is conducted to the job substrate. The foremost reason behind the growth of HAZ around the machining zone is the transfer of thermal energy to the job substrate. Combined effects of influences of voltage applied, duty factor, pulse frequency and electrolyte concentration on HAZ area are exhibited in Figs. 4 (i) and (ii). The surface plot i.e. Fig. 4(i) reflects that the applied voltage has a linear correlation with HAZ area at fixed electrolyte concentration. Duty ratio and pulse frequency are considered as fixed value of 50% and 600Hz respectively. HAZ

respectively, overcut becomes higher at 50V/30wt%. If the voltage and electrolyte concentration are fixed at 45 V and 25wt%, overcut increases with increase in duty ratio up to 50% and after that it decreases. Also overcut decreases when pulse frequency increases and becomes higher at 45V/60%/25wt%/200Hz. Based on the empirical model i.e. Eq. (3) it can be said that the minimized overcut of 82.333 μm can be achieved at 35V/26wt%NaOH/60%/1000Hz, which is obtained using MINITAB software and depicted in Fig. 3(iii). For minimising overcut equal weightage is assigned on the target and upper limit of linear desirability function. The weighted

area almost steadily enlarges with boost of applied voltage, electrolyte concentration that influences the production of thermal energy and it becomes higher at 55V/30 wt%. Fig. 4(ii) reveals that by increasing the duty ratio past 50 % and by bumping up the pulse frequency upto 600 Hz HAZ area is contracted. But HAZ area is increased with duty ratio upto 50% and increasing of pulse frequency beyond 600 Hz. On the basis of Eq. (4) and using the MINITAB software the minimized HAZ area can be found as 160.76×10^3 μm^2 at the parametric combination of 55V/25wt%NaOH/60%/644Hz and shown in Fig. 4 (iii).



(i) Effects of applied voltage and electrolyte concentration on HAZ area

(ii) Effects of duty ratio and pulse frequency on HAZ area

(iii) Optimisation results for minimised HAZ area

Fig. 4. Effects of process parameters on HAZ area.

produces irregularities on the surface of job that worsen the surface smoothness of the µ-channels. If spark discharges are uniform and continuous and the number of secondary sparking is small, the surface finish could be improved. From the Fig. 5, it is observed that if the pulse frequency is increased, initially the surface roughness is decreased because the rates of stray and secondary sparking are reduced on account of decrease in pulse on-time. But, it is very difficult to control the non-uniform stray and secondary sparkings that cause irregularities on the machining surface at higher pulse frequency. So, after that the surface roughness is enhanced and the minimum surface roughness (R_a) of 0.9638µm is attained at 5V/30wt% NaOH/60%/660Hz as shown in Fig. 5(iii).

4.3 Multi - objective optimization during micro-channelling on glass

Multi-objective optimisation analysis for micro-channeling on glass was performed with the help of MINITAB 16 software and the optimised outcome for MRR, OC, HAZ and R_a are exhibited in Figs. 6(i) and (ii). MRR, OC, HAZ and R_a are optimised altogether in one setting and depicted in Fig. 6(i) in which a process variable is represented by each column of the graph and a response variable is represented by each row of the graph represents in each cell of the graph. The numerical values at the top of a column indicate the high, present and low parameter level settings of the experimental design. The optimum and predicted responses, 'y_u' at present parametric combinations and individual desirability score are shown at the left of each row. The current parametric combinations are found as applied voltage of 35V, electrolyte

(iv). Effects of process variables on surface roughness

The influences of process variables on surface roughness (i.e. R_a) when micro-channelling operation is done on glass using NaOH electrolyte and spring feed mechanism at fixed inter-electrode gap of 40 mm are shown in Figs. 5 (i) and (ii). The Fig. 5 clearly indicates that surface roughness enhances due to intensification in sparking rate as voltage and electrolyte concentration are increased but it decreases only after 50 V and 55% duty ratio. The crater size in the machining area increases with increment in heat into the machined channel during sparking. Also the bombardment of electrons during spark discharges

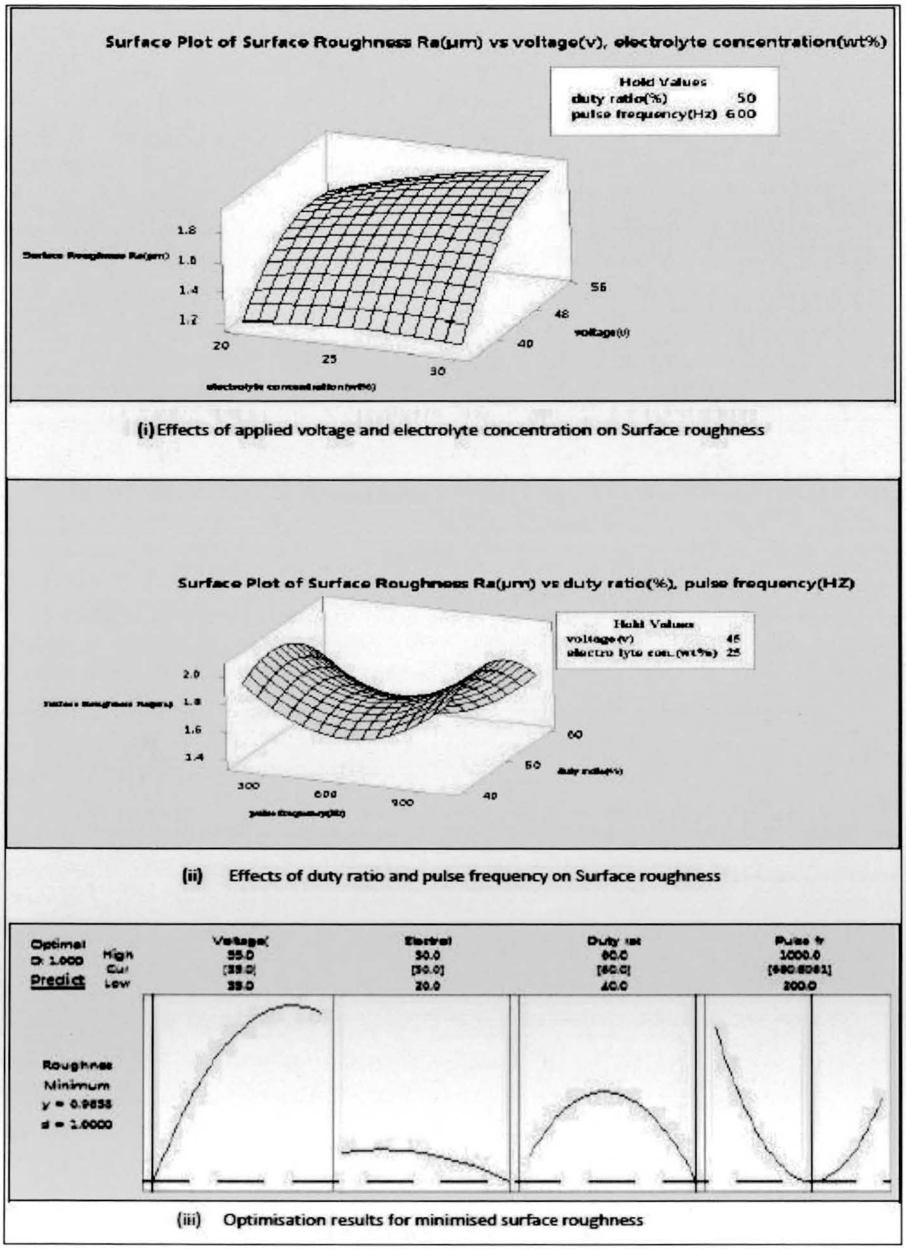
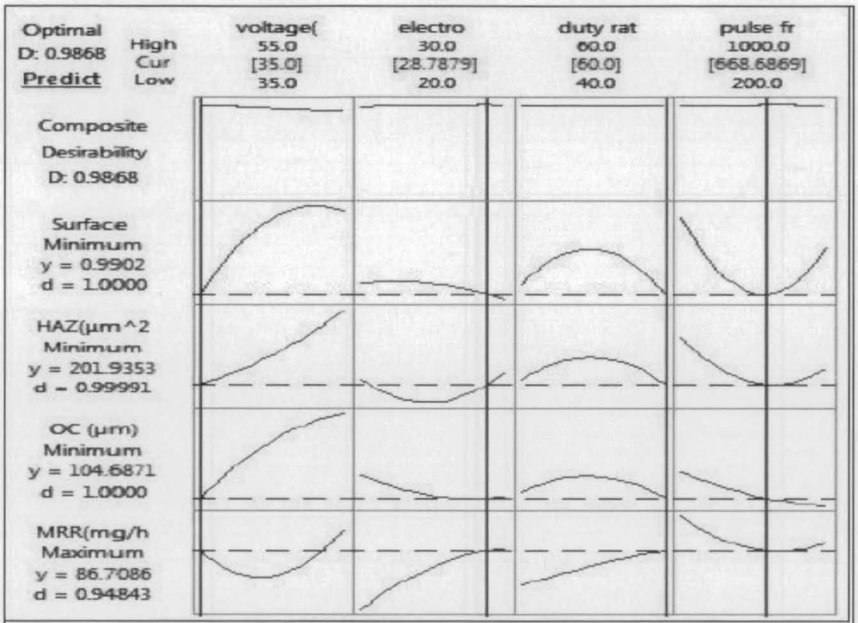


Fig. 5. Effects of process parameters on surface roughness.

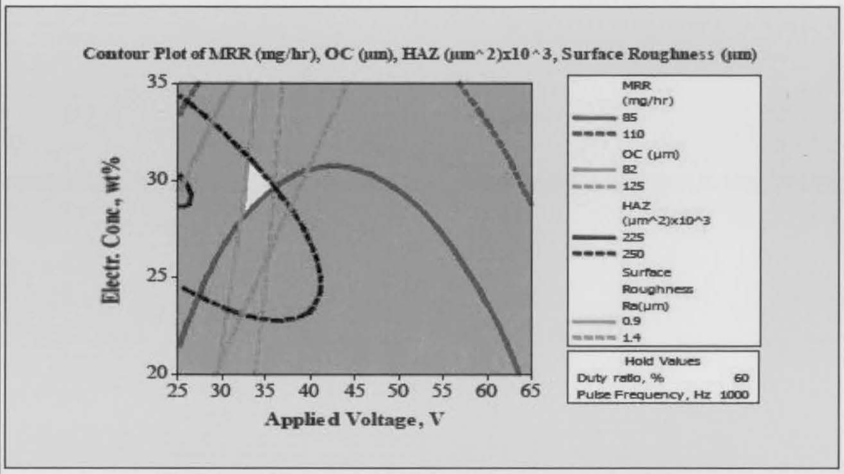
concentration of 28.7879wt%, duty ratio 60% and pulse frequency of 668.6869 Hz for achieving predicted optimum value of MRR (Y_{MRR}) of 86.7086 mg/hr, OC (y_{OC}) of 104.68 µm, HAZ area (Y_{HAZ}) of 201.9353 x 103µm^2 and R_a (Y_{R_a}) of 0.9902µm. The composite desirability, D [23] is highlighted at the top left corner of the graph with a value of 0.9868, which is very close to 1. The composite desirability label corresponds to the current combination and changes for shifting the process variable combinations interactively. The label is also optimal when the optimisation plot is developed. The current parametric settings are represented by vertical lines inside the graph and the current response values by the horizontal dotted lines.

Fig. 6(ii) shows the overlaid contour plot and white area, which reveals the feasible region. The feasible region is formed by two significant process variables i.e., applied voltage, electrolyte concentration keeping other design variables i.e., duty ratio and pulse frequency fixed so that the acceptable values of each response are laid within their respective contours. The feasible region considered for MRR is 85mg/hr as upper value and 110mg/hr as lower value respectively. For OC, HAZ area and R_a the upper and lower values are chosen as 82µm & 125µm, 225 x 10^{3}µm^2 & 250 x 10^{3}µm^2 and 0.9 µm & 1.4 µm respectively. The other two process variables i.e. pulse frequency and duty ratio are set kept fixed at 60% and 1000 Hz respectively. (Ref. Fig. 6.)

Figs. 7(a) and (b) show the optical and SEM images of µ-channel respectively cut at 35V/28wt%/60%/668Hz. The profile of machined surface of micro-channel obtained at 35V/28wt%/60%/668Hz on glass is shown in Fig. 8(i) as graphical representation. Fig. 8(ii) represents the XRD pattern of micro-channels on glass cut at 35V/28wt%/60%/668Hz. The XRD pattern of glass does not show any peak because it is amorphous. After micro-channel cutting on glass, the intensity (CPC) has slightly been decreased but the property of glass after machining is found unchanged as the chemical reactions take place in NaOH electrolyte solution where major element is sodium, which is also present in glass. But debris, micro-crater and thermal effect have been observed and shown in Fig. 7(c). (Ref. Fig. 7 and 8.)



(i) Multi-objective optimization of process parameters based on RSM



(ii) Overlaid contour plot for MRR, OC, HAZ area and R_a based on RSM

Fig. 6. Multi-objective optimisation results for different performance criteria based on RSM.

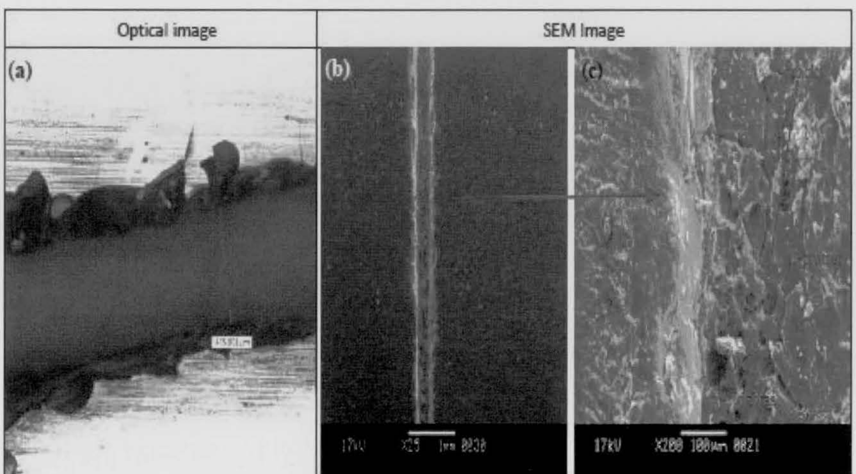
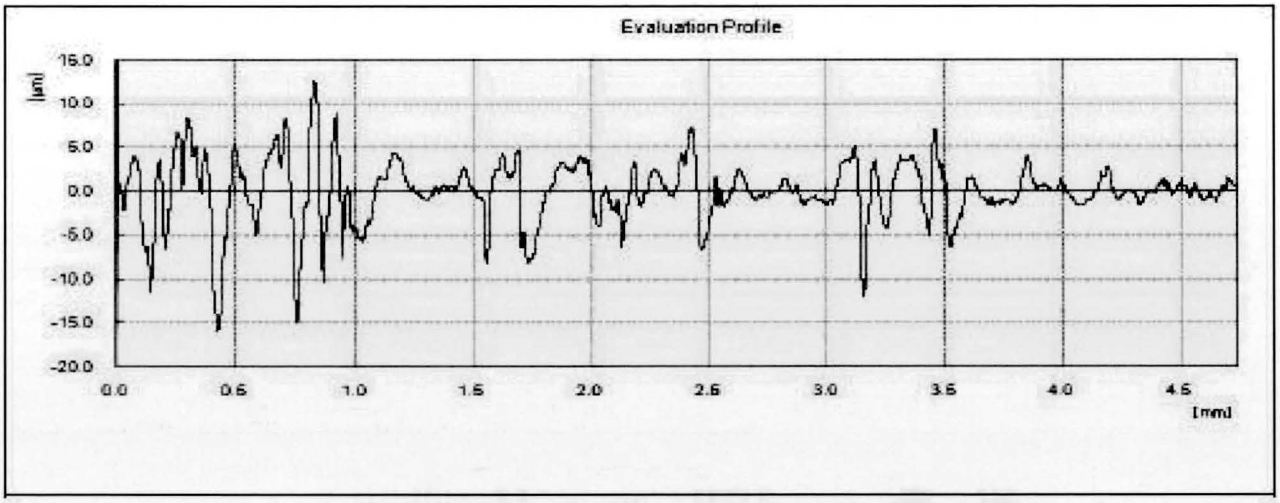


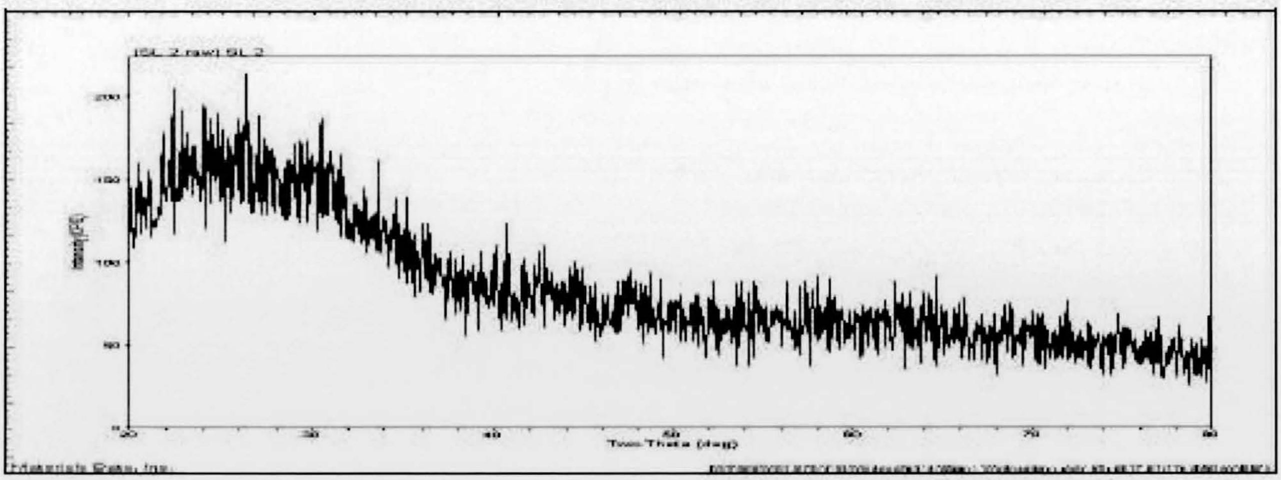
Fig. 7. Micro-channel on glass at 35V/28wt%/60%/668Hz.

5. Conclusions

After this investigation it can be concluded that the developed ECDM system can be used successfully for micro-channel cutting applications on glass using spring feed mechanism and the process variables can be controlled optimally for attaining maximum MRR and minimum OC, HAZ area and surface roughness. For micro-channeling on glass with micro-ECDM voltage has strong major effect on the responses, i.e., MRR, OC, HAZ area and Ra and is predominant over other process variables. With the rise of applied voltage, duty ratio and electrolyte concentration MRR enhances but decreases with pulse frequency during micro-channel cutting on glass using NaOH as electrolyte. Width-of-cut of micro-channels always increases with raise of applied voltage, electrolyte concentration, so OC increases but it gets smaller with bumping up of pulse frequency upto 600Hz and enhances again after that. With rise of applied voltage, electrolyte concentration and duty ratio HAZ area almost steadily enlarges and becomes wider at 55V and 30 wt% electrolyte concentration. But the heat affected zone area is decreased after 50% of duty ratio and with the increase of pulse frequency beyond 600Hz. If frequency is increased, initially the surface roughness decreases but it is very difficult to control the stray and secondary sparking at upper level of pulse frequency that produces irregularities on the machining surface and makes the surface rougher. MRR is found maximum at 55V/30wt%NaOH/40%/200Hz and better surface quality of micro-channel can be achieved with higher machining depth



(i) surface profile of micro-channel at 35V/28wt%/60%/668Hz



(ii) XRD pattern of machined surface of micro-channel at 35V/28wt%/60%/668Hz

Fig. 8. Surface condition of micro-channel on glass at 35V/28wt%/60%/668Hz.

at 35V/30wt%NaOH/60%/660Hz. The present set of developed empirical models and optimal analyses will be greatly important and constructive for achieving high quality precision micro-channeling on glass by micro-ECDM process. There are future scopes of research work to identify the optimal micro-ECDM process parameter combination for other important machining criteria such as shape geometry of micro-channel, micro-crack and surface morphology etc of micro-channel for other electrically non-conducting materials such as ceramics etc.

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References

1. Basak, I; Ghosh, A: Mechanism of spark generation during electrochemical discharge machining: A theoretical model and experimental verification, 'Journal of Materials Processing Technology', vol. 62, 1996, 46-53, DOI: 10.1016/0924-0136(95)02202-3.
2. Bhattacharyya, B; Doloi, B; Sorkhel, SK: Experimental investigations into electrochemical discharge machining (ECDM) of non-conductive ceramic materials, 'Journal of Materials Processing Technology', vol. 95, 1999, 145-154, DOI: 10.1016/S0924-0136(99)00318-0.
3. Jain, VK; Dixit, PM & Pandey, PM: On the analysis of the electrochemical spark machining process, 'International Journal of Machine Tools & Manufacture', vol. 39, 1999, 165 – 186,

DOI: 10.1016/S0890-6955(98)00010-8.

4. Elhami, S & Razfar, MR: Analytical and experimental study on the integration of ultrasonically vibrated tool into the micro electro-chemical discharge drilling, 'Precision Engineering', vol. 47, 2017, 424-433, DOI: 10.1016/j.precisioneng.2016.09.015.
5. Elhami, S & Razfar, MR: Effect of ultrasonic vibration on the single discharge of electrochemical discharge machining, Materials and Manufacturing Processes", vol. 33, no. 4, 2018, 444-451, DOI: 10.1080/10426914.2017.1328113.
6. Singh, T & Dvivedi, A: On pressurized feeding approach for effective control on working gap in ECDM, Materials and Manufacturing Processes', vol. 33, no. 4, 2018, 462-473, DOI: 10.1080/10426914.2017.1339319.
7. Tang, W; Kang, X & Zhao, W: Enhancement of electrochemical discharge machining accuracy and surface integrity using side-insulated tool electrode with diamond coating, 'Journal of Micromechanics and Microengineering', vol. 27, 2017, pp11, DOI: 10.1088/13616439aa6e94.
8. Mallick, B; Sarkar, BR; Doloi, B & Bhattacharyya, B: Analysis on electrochemical discharge machining during micro-channel cutting on glass, 'International Journal of Precision Technology', vol. 7, 2017, 32-50, DOI: 10.1504/IJPTECH.2017.084554.
9. Han, M; Chae, KW; Min, BK: Fabrication of high-aspect-ratio microgrooves using an electrochemical discharge micro milling process, 'Journal of Micromechanics and Microengineering', vol. 27, 2017, pp.5, DOI:10.1088/1361-6439/aa64b9.
10. Hajian, M; Razfar, MR & Movahed, S: An experimental study on the effect of magnetic field orientations and electrolyte concentrations on ECDM milling performance of glass, 'Precision Engg', vol.45, 2016, 322-331, DOI:10.1016jprecisioneng.2016.01.007.
11. Saranya, S; Nair, A & Ravisankar, A: Experimental investigations on the electrical and 2D-machining characteristics of an electrochemical discharge machining (ECDM) process, 'Microsystem Technologies', vol. 22, 2016, 1-9, DOI 10.1007/s00542-016-3027-8.
12. Baoyang, J; Shuhuai, L; Kevin, W & Jun, N: Modeling and experimental investigation of gas film in micro-electrochemical discharge machining process, 'International Journal of Machine Tools and Manufacture', vol. 90, 2015. 8-15, DOI: 10.1016/j.ijmachtools.2014.11.006.
13. Mallick, B; Sarkar, BR; Doloi, B & Bhattacharyya, B: Multi criteria optimization of electrochemical discharge micro-machining process during micro-channel generation on glass. Applied Mechanics and Materials, 592-594, 525-529, 2014, DOI: 10.4028/www.scientific.net/AMM.592-594.525
14. Cao, XD; Kim, BY & Chu, CN: Hybrid micromachining of glass using ECDM and micro grinding. International Journal of Precision Engineering and Manufacturing, vol. 14 no. 1, 2013, 5-10, DOI: 10.1007/s12541-013-0001-6.
15. Cheng, CP; Wu, KL; Mai, C.C; Hsu, Y.S. & Yan, B.H. (2010). Magnetic field assisted electrochemical discharge machining. Journal of Micromechanics & Microengineering, 20, 075019 (7pp), DOI: 10.1088/0960-1317/20/7/075019
16. Sarkar, BR; Doloi, B; & Bhattacharyya, B: Experimental investigation into electrochemical discharge micro drilling on advanced ceramics. International Journal of Manufacturing Technology and Management, vol. 13, no. 2/3/4, 2008 214-225, DOI: 10.1504/IJMTM.2008.016772.
17. Sarkar, B.R; Doloi, B. & Bhattacharyya, B. (2009). Investigation into the influences of the power circuit on the micro-electrochemical discharge machining process. Proceedings of the Institution of Mechanical Engineers, Part B: 'Journal of Engineering Manufacture', vol. 223, no. 2, 133 –144, DOI:10.1243/09544054JEM1258.
18. Zheng, ZP; Su, HC; Huang, FY & Yan, BH: (2007), The tool geometrical shape and pulse- off time of pulse voltage effects in a Pyrex glass electrochemical discharge micro drilling process, 'Journal of Micromechanics & Microengineering', vol. 17, no. 2, 265-272, DOI:10.1088/0960-1317/17/2/012.
19. Sarkar, BR; Doloi, B; Bhattacharyya, B: 2006 Parametric analysis on electrochemical discharge machining of silicon nitride ceramic, 'Intl Journal Advanced Manufacturing Technology, vol. 28, no. 9, 873-881, DOI: 10.1007/s00170-004-2448-1.
20. Sarkar, BR; Doloi, B; Bhattacharyya, B: Investigation on electrochemical discharge micro-machining of silicon carbide. 'Intl Journal of Material Forming and Machining Processes', vol. 4, no. 2, 2017, 29-44,. DOI: 10.4018/IJMFMP.2017070103
21. Antil, P: Modelling and Multi-objective optimization during ECDM of silicon carbide reinforced epoxy composites, 'Silicon', 2019,

https://doi.org/10.1007/s12633-019-00122-8.

22. Ladeesh, VG & Manu, R: Performance evaluation and multi response optimization of grinding aided electrochemical discharge drilling (G ECDD) of borosilicate glass. Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 40, no. 568, 2018, 19, DOI: 10.1007/s40430-018-1489-6.
23. Montgomery, DC: Design and analysis of experiments. Singapore, John Wiley & Sons, 1997 ◘

Bijan Mallick, Assistant Prof. of Techno International Batanagar and was a Research Scholar of Production Engineering Department, Jadavpur University, Kolkata, till 2013 under BSR fellowship scheme of UGC. He has more than 8 years research as well as teaching experience. He has published more than 5 research articles in reputed journals and presented many research works in international conferences. His research interest includes micro-machining and ECDM processes.

Dr. Biplab Ranjan Sarkar, Associate Prof. of Production Engg Dept., Jadavpur University, Kolkata. He has published more than 30 international research papers including 15 research papers in reputed international journals. He has presented more than 15 papers in many prestigious conferences. He has guided several MTech theses and supervising PhD theses. His areas of research interest include nonconventional machining processes such as electrical discharge machining (EDM), electrochemical discharge machining (ECDM) and micro-machining of advanced materials, etc.

Dr. Biswanath Doloi, Prof. & former Head of Prod. Engg Dept. of Jadavpur University. He obtained PhD (Engineering) from 'Jadavpur University'. He is co-Principal investigator of DST sponsored research project on Wire Electrochemical Micro-machining. He published more than 65 papers in international and national journals in the area of advanced Manufacturing Technology and presented more than 116 research papers in reputed national and international seminar and conferences. He has guided 12 PhD's out of 8 PhD's awarded. He has visited international institutes like Cranfield University, UK, National University of Singapore(NUS), Singapore, Polytechnic University of Hongkong, Hongkong City University, Asian Institute of Technology (AIT), Bangkok and IIUM, Malaysia. He received Young Scientist Award from DST, New Delhi, 2002. He had undergone international training on Advanced Product Design and Development especially 3D Printing technology at AIT Bangkok.

Dr. Bijoy Bhattacharyya, FINAE, professor and former Head of the Production Engg Dept. and Coordinator of Center of Advance Study Programme under University Grants Commission and Quality Improvement Programme under AICTE of Jadavpur University. His research areas include non-traditional machining, micro machining, advanced manufacturing systems, etc. He has published 108 research papers in National and International Journals and 271 research papers in National and International Conferences. He has published several book chapters and conference proceedings. Recently, he has published one book titled "Electrochemical Micromachining for Nanofabrication, MEMS and Nanotechnology", William Andrew Applied Science Publishers, Micro & Nano Technologies Series, Elsevier Inc, USA. Several PhD's have been awarded under his guidance. He has completed several research projects. He is recipient of various awards, e.g. Gold Medal and Certificate of Achievements for research papers and thesis as well as the Career Award of the UGC, New Delhi.