EXPERIMENTAL STUDY ON THE MRR, MACHINED DEPTH AND HOLE DIAMETER FOR SODA-LIME GLASS BY ELECTROCHEMICAL DISCHARGE MACHINING PROCESS WITH COPPER TOOL

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Abstract: The electrochemical discharge machining (ECDM) is an integrated machining process that can cut effectively with various non-conducting materials. In present research work, the copper tool was used as a cathode to machined Soda-lime glass workpiece material by fabricated ECDM setup. The Soda-lime glass material is having high brittleness and hardness properties. Taguchi L_{27} orthogonal array method was used for drilling experimentation on Soda-lime glass by ECDM. The Minitab software was utilized for analyzing the experimental output results. The average material removal rate (MRR), average hole diameter and average machined depth were considered as output responses and input parameters were electrolyte concentration, voltage, and tool rotation speed. The experimental and analytical results were showing that for average material removal rate, electrolyte concentration was the most dominating factor followed by voltage and tool electrode rotation. However, for average machined depth, the voltage was the most powerful parameter, then after electrolyte concentration and tool rotation. Though, for average hole diameter, tool rotation was the most powerful parameter followed by electrolyte concentration and voltage. The response surface methodology plot shows that the optimum values of input parameters were voltage of 75 V, electrolyte concentration of 11.21 %, and rotation of 50 r/min, to get the higher average material removal rate, maximum average machined depth and targeted nominal average hole diameter.

Key words: ECDM, Soda-lime glass, Taguchi, Copper

1. INTRODUCTION

The micro-channels have used in Biomedical Systems, Micro-Electro Mechanical system (MEMS), Micro Chemical Reactor (MCR). These micro-channels could also be used in the making of miniaturized devices like chemical reactors and heat exchangers. The miniaturized devices are made up of some materials such as glass, ceramic, etc. [2]. The Soda-lime glass is one of the types of glass material. It is widely used in the production of mirrors, printed circuit substrates, micro-electromechanical systems, wafers, data storage disks, chemical apparatus, touch screens, photo masks, microscopic slides, optical windows, microfluidic devices, and camera lens. It is a tough task to machine this material due to its various properties such as high hardness, high electrical resistivity, high brittleness, non-porosity, durability, biocompatibility, temperature stability, optical transparency, homogeneity, corrosion resistance, and low thermal coefficient expansion. This material can be machined by using various machining processes such as laser machining, precision milling process, compound machining process, precision lathe machining process, abrasive jet machining process, micro-grinding process, microwave drilling process and electrochemical discharge machining processes [16]. The electrochemical discharge machining process is a hybrid process that combined with two processes, i.e. electrochemical and electro-discharge processes which can efficiently cut glass material [27]. The ECDM process can be used for the machining of miniature components, repairing of copper tracks on printed circuit boards, fabrication of micro-filters, heat treatment, micro-channels, arrays of holes in non-conducting material, Hydrogen gas formation, surface modification and nanoparticle formation [18]. The Electrochemical discharge fact was investigated first time in the year 1968 by Kurafuji et al. and successfully micro-holes in glass material [11]. The increasing applied voltage increases the hole diameters because the quantity of effective thermal energy is increased that removes more material, these smaller micro-holes are primarily required in MEMS systems [1]. The micro-holes and micro-channels were produced on Soda-lime glass and borosilicate glass material using ECDM process. The optimized input process parameters were investigated for better results of material erosion rate, tool wear and radial overcut [12]. L. Paul et al. developed micro-channels in Soda-lime glass material using copper wire as a tool. They found that the material removal rate increased with increasing in voltage and electrolyte temperature [13]. The lathe types electrochemical discharge machine was used to machine the Soda-lime glass rod using a thin tungsten rod. The width and depth of the machined micro grooves, as well as surface roughness of machined Soda-lime glass, were increased with an increase in voltage [6]. Sabahi et al. machined micro-channels on glass with different machining conditions. They found that a magnetic field-assisted electrolyte concentration promotes to enrich the hardness of the micro-channel edge [25]. The precise micro holes were produced on borosilicate glass with higher machining voltage and electrolyte temperature [28]. The increased machining depth was achieved by using abrasive cutting tools in the ECDM drilling process on alumina and borosilicate glass [8]. In the field of the electrochemical discharge machining process, the many researchers have used Graphite as anode tool material, cathode tool as a Tungsten carbide material, and NaOH as an electrolyte medium [15]. In this research report, discuss the experimentation for soda-lime glass by the ECDM process with the copper cathode tool electrode. The experimental results were further analyzed and optimized with response surface methodology. In this research work, each experiment is repeated twice and taking its average value of output responses. The input parameters were taken as voltage, tool rotation, and concentration of electrolyte. The output responses are average material removal rate, average hole diameter, and average machined depth. Previously, Pawar et al. have used fabricated ECDM machine was used for machining of mosaic ceramic material [17], silicon carbide material [21], and soda-lime glass material [19, 22] with different input process parameters as well as tool materials.

2. MATERIALS AND METHODS

Figure 1 indicates the operational principle of the ECDM process.

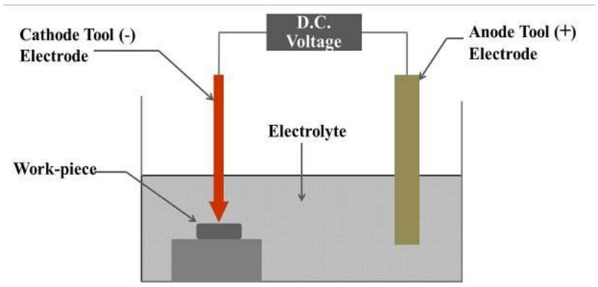


Fig. 1. Schematic diagram of the ECDM process [26]

In this method anode, cathode, and workpiece material are dipped inside an aqueous electrolyte medium. When D.C. voltage approximately near about 35 V provided in between anode and cathode tool then electrolysis has resulted. Then, hydrogen gas bubbles and oxygen bubbles are formed at the cathode and anode tool electrodes. When the voltage is elevated, the current increases and a large number of bubbles developed a bubble layer around the anode as well as a cathode. The bubbles have coalesced toward a gas film at the rounded surface of the cathode tool while voltage extreme than the critical voltage. At that time light emission was sighted and electrical discharges occur [14, 27]. The fabricated ECDM machine was used for machining of soda-lime glass material. The movement of all axes, i.e. X, Y and Z axes were controlled manually. The workpiece was situated on the fixture and the fixture was located on electrolyte container. The gravity feeding mechanism was applied to the workpiece to move in an upward direction during the ECDM process. The cathode was coupled to the stepper motor spindle and its rotation was controlled by the Arduino Uno board through the laptop. The D.C. voltage was supplied between the anode and cathode tool electrodes [20]. The conical-shaped copper cathode electrode tool tip diameter of 1mm and raised to 3mm diameter was utilized. The stainless steel 416 material rod was taken as the anode tool having 15 mm in diameter. For current experimental work, NaOH electrolyte was used, also machining time period set to 25 min for each experiment. The micro drilled holes on 150×140×3 mm^3 Soda-lime glass material were done through the copper tool in the ECDM process. The experimentations were done on Soda-lime glass material by using Taguchi L_{27} orthogonal array technique. In this experimental work selecting three factors with three levels and the two-way interactions takes place as a result, the 18 total degrees of freedom. For that reason, the experimental work L_{27} orthogonal array was used which assists 26 degrees of freedom [5]. The response surface methodology approach was used for the optimization of input process parameters to obtain better output responses.

3. RESULTS AND DISCUSSION

In current experimental work voltage, tool rotation and concentration of electrolyte are considered as input factors and output responses are average hole diameter, average material removal rate and average machining depth. Table 1 designates those input process parameters and their separate levels.

Table 1. Input parameters and their Levels

Factor	Input Parameters	Unit	Levels		
			1	2	3
A	Voltage	(V)	55	65	75
B	Electrolyte Concentration	(%)	10	15	20
C	Tool Rotation	(r/min)	0	20	50

The material removal rate was measured by using a precision weight machine and the following equation (1) was used to calculate the MRR.

$$\mathrm{MRR} = \frac{(Iw)w - (Fw)w}{t} \tag{1}$$

Where, $(Iw)_w$ = Initial weight of workpiece, mg, $(Fw)_w$= Final weight of workpiece, mg, t= Machining time in min.

The hole diameter and machined depth were measured by using a digital Vernier scale. The average values of all output responses were taken from one experiment was repeated twice and taking its average value of output responses known as average material removal rate, average hole diameter, and average machined depth. Figure 2 shows the results of machined holes on soda-lime glass with a copper tool in the ECDM process. Figure 3 shows the replicated results of machined holes on soda-lime glass with a copper tool in the ECDM process. It shows, the tool rotation of 0 r/min, at that condition the average hole diameter was the irregular or uneven round shape and at 50 r/min tool rotation results show the regular round shape of average hole diameter.

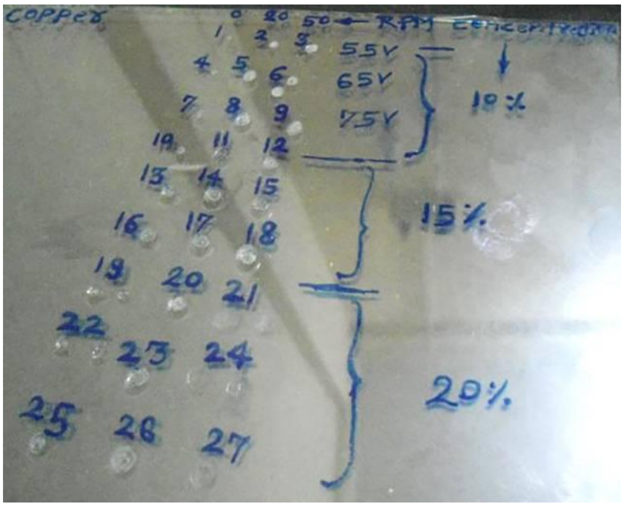


Fig. 2. Experiments on Soda-lime glass (results 1) by a Copper tool

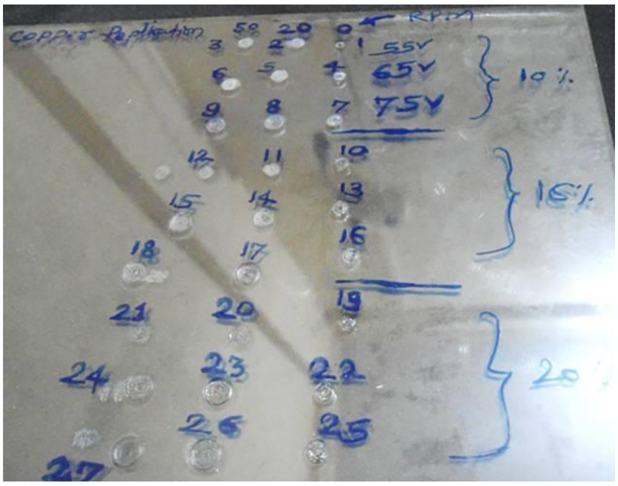


Fig. 3. Experiments on Soda-lime glass (results 2) (replicated) by Copper tool

Table 2 shows the sparking intensities during the machining of Soda-lime glass through the copper tool for each experiment in the ECDM process. Table 2 is constructed according to Taguchi L_{27} orthogonal array method and it includes each machining experimental condition and their individual sparking intensity. During the ECDM drilling on Soda-lime glass material by using a copper tool. It is observed that when the applied voltage between cathode and anode the bubbles generated because of electrochemical liberated H_2 and water vapour created by ohmic heating at the tool electrode interface. The isolation between the electrode and the electrolyte takes place. The isolation between the electrode and the electrolyte leads to discharge due to switching, where the switching e.m.f. The high electric field source sparks within the gas bubble isolating the tip. The spark should arise between the tip of the tool electrode and the inner surface of the electrolyte. At the instant when sparks ensues, an avalanche of electrons initiated by ionization flow towards the workpiece kept around 20 μm distances away from the tool tip. It is a drifting phenomenon of the electron avalanche and therefore this process is discrete and repetitive. The bombardment of electrons on the glass workpiece surface results in intense heating due to the discharge process and therefore material removal takes place [3, 9, 10]. The sparking intensity was greater when the increase in electrolyte concentration and voltage which causes an increase in the average material removal rate, average hole diameter, and average machined depth.

Table 3 indicates that different micro-holes geometries at 100X magnification conditions using a fluorescence optical microscope. Each micro-hole image shows that each experimental condition, according to Taguchi L_{27} orthogonal array. It shows that at the 0 r/min condition the average hole diameter is not perfectly round shape, due to discharge focused mostly on the tip of tool electrode and at the round surface of the tool electrode was intermittently hence, it is irregular hole geometry. Also, when a rise in the voltage and electrolyte concentration, then average hole diameters also increase due to the intensity of spark discharge increases in the ECDM drilling process [4]. The tool tip can generate an indent at the start of machining, which is an indication of the tool in ECDM. The distribution of discharge energy is more uniform when the electrode rotates. On the one hand, a high tool rotation rate can deteriorate the discharge effect, thus dropping excessive sparks. A higher rotational rate avoids the discharge focuses on the same points and improves the dimensional precision of micro-holes. The rotation of the electrode enhances the roundness of a micro-hole.

Table 4 shows that observed experimental results after ECDM machining of Soda-lime glass using a copper tool. Each experiments were repeated twice and taking its average value of output responses which is presented in Table 4. The output responses are average material removal rate, average hole diameter and average machined depth.

Table 2. Sparking intensities for machining of Soda-lime glass through Copper tool material

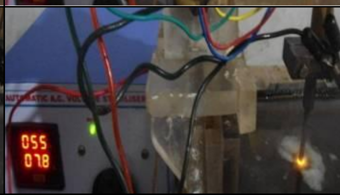
Experiments on Soda-lime glass through Copper tool electrode				
Tool Rotation (r/min)			Voltage	Conc.
0	20	50	(V)	(%)
			55	
			65	10
			75	
			55	
			65	15
			75	
			55	
			65	20
			75	

Table 3. Microscopic images of drilled micro-holes on Soda-lime glass material by using Copper tool electrode

Copper Tool Experimental Results 1			Copper Tool Experimental Results 2				
Rotation (r/min)			Rotation (r/min)			Volt	Conc.
0	20	50	0	20	50	(V)	(%)
0.77	1.76	2.01	1.48	2.72	2.83	55	10
0.99	2.50	2.32	1.75	2.92	3.01	65	
1.21	2.76	2.82	2.40	3.65	3.51	75	
1.31	2.73	2.76	2.38	2.88	2.75	55	15
2.2	2.88	2.80	2.47	3.58	3.71	65	
2.64	3.10	3.38	2.60	3.98	4.05	75	
2.34	3.16	3.30	2.51	3.40	3.54	55	20
2.41	3.30	3.45	2.82	3.97	4.19	65	
2.85	4.10	4.27	3.04	4.30	4.45	75	

Table 4. Taguchi L_{27} orthogonal array machining conditions and their results

Run	Conc. (%)	Voltage (V)	Rotation (r/min)	MRR1 (mg/min)	MRR2 (mg/min)	Average MRR (mg/min)	Hole Dia. 1 (mm)	Hole Dia.2 (mm)	Average Hole Dia. (mm)	Machined Depth 1 (mm)	Machined Depth 2 (mm)	Average Machined Depth (mm)
1	10	55	0	0	0.1	0.05	0.77	1.48	1.125	0.08	0.08	0.08
2	10	55	20	0.1	0.15	0.125	1.76	2.72	2.24	0.10	0.09	0.095
3	10	55	50	0.17	0.20	0.185	2.01	2.83	2.42	0.21	0.15	0.18
4	10	65	0	0.1	0.17	0.135	0.99	1.75	1.37	0.09	0.14	0.115
5	10	65	20	0.21	0.27	0.24	2.50	2.92	2.71	0.38	0.40	0.39
6	10	65	50	0.19	0.27	0.23	2.32	3.01	2.665	0.34	0.35	0.345
7	10	75	0	0.14	0.22	0.18	1.21	2.40	1.805	0.10	0.30	0.2
8	10	75	20	0.25	0.35	0.3	2.76	3.65	3.205	0.44	0.60	0.52
9	10	75	50	0.31	0.39	0.35	2.82	3.51	3.165	0.57	0.67	0.62
10	15	55	0	0.15	0.17	0.16	1.31	2.38	1.845	0.12	0.15	0.135
11	15	55	20	0.22	0.20	0.21	2.73	2.88	2.805	0.37	0.22	0.295
12	15	55	50	0.27	0.25	0.26	2.76	2.75	2.755	0.40	0.31	0.355
13	15	65	0	0.22	0.23	0.225	2.23	2.47	2.35	0.28	0.30	0.29
14	15	65	20	0.31	0.32	0.315	2.88	3.58	3.23	0.57	0.52	0.545
15	15	65	50	0.30	0.33	0.315	2.80	3.71	3.255	0.54	0.48	0.51
16	15	75	0	0.26	0.25	0.255	2.64	2.60	2.62	0.49	0.41	0.45
17	15	75	20	0.35	0.42	0.385	3.10	3.98	3.54	0.73	0.70	0.715
18	15	75	50	0.40	0.43	0.415	3.38	4.05	3.715	0.80	0.78	0.79
19	20	55	0	0.24	0.26	0.25	2.34	2.51	2.425	0.23	0.32	0.275
20	20	55	20	0.33	0.34	0.335	3.16	3.40	3.28	0.59	0.51	0.55
21	20	55	50	0.32	0.33	0.325	3.30	3.54	3.42	0.44	0.46	0.45
22	20	65	0	0.23	0.28	0.255	2.41	2.82	2.615	0.27	0.40	0.335
23	20	65	20	0.38	0.40	0.39	3.30	3.97	3.635	0.64	0.59	0.615
24	20	65	50	0.39	0.43	0.41	3.45	4.19	3.82	0.67	0.66	0.665
25	20	75	0	0.30	0.29	0.295	2.85	3.04	2.945	0.42	0.50	0.46
26	20	75	20	0.46	0.48	0.47	4.10	4.30	4.2	1.01	0.99	1
27	20	75	50	0.48	0.49	0.485	4.27	4.45	4.36	0.98	0.94	0.96

3.1 ANOVA Statistical Analysis

The effect of input process parameters on output responses are investigated. The ANOVA statistical tool is used to analyze the most important input factor. The output response table is used to investigate the leading position of input process factors. The signal to noise (S/N) ratio was preferred, depending on the earlier research work evidence. The signal defines the outcome of each factor of the response, while noise is the measure of the influence of deviation as of average responses. In this work, for average hole diameter S/N ratio criteria were selected as nominal is best because the average of machined hole diameter results was considered and the targeted nominal of average machined hole diameter is set to 3.00 mm. In this analysis, the average material removal rate and average machining depth were considered as larger-the-better criteria. The S/N ratio was assessed by utilizing the formula shown in equation (2) and equation (3) [24].

For larger is better

$$S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (2)$$

For nominal is best

$$S/N = 10\log\left(\frac{\bar{y}^2}{s_y^2}\right) \quad (3)$$

Where $\bar{y}$ the average of observed data is, s_y^2 is the variance of y, y is the observed data and the number of observations is represented as n.

3.2 Analysis of average MRR of Soda-lime glass through Copper tool material

Table 5 represents the ANOVA table for average MRR using Copper tool material in which the desirability condition of larger is better. It denotes the maximum F-value 95.40 was found in electrolyte concentration which indicates it is the utmost powerful factor related to the other two input factors. It's caused by increasing electrolyte concentration increases the conductivity of electrolytes and therefore, it heightens the chemical etching process and material removal rate [7]. The p values for all three input factors are lower than 0.05 which indicates that all parameters are significant. The electrolyte concentration contributes 37.96%, tool rotation is providing 29.37% and voltage is contributing 28.69% respectively. The present results show that good agreements with the previous results were reported for glass and Silicon wafer materials [8, 14]. Table 6 indicates the output response table for the signal to noise (S/N) ratios of average MRR of Soda-lime glass material using copper tool material. It shows that electrolyte concentration is the first position, then voltage and lastly the tool rotation.

Table 5. ANOVA table for average MRR of Soda-lime glass through Copper tool

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Percentage Contribution
Voltage	2	0.08474	0.04237	72.10	<0.001	28.69
Electrolyte Conc.	2	0.11211	0.05606	95.40	<0.001	37.96
Rotation Speed	2	0.08675	0.04337	73.82	<0.001	29.37
Error	20	0.01175	0.00059			3.98
Total	26	0.29535				100

Table 6. Response table for signal to noise (S/N) ratios for average MRR of Soda-lime glass through the Copper tool

Level	Electrolyte Concentration	Voltage	Rotation Speed
1	-15.085	-14.579	-14.841
2	-11.333	-11.486	-10.781
3	-9.171	-9.524	-9.967
Delta	5.914	5.055	4.873
Rank	1	2	3

The main effect plot shown in Figure 4 specifies that the average MRR rises when increases in voltage, the concentration of electrolyte and tool rotation. The higher average MRR achieved at ECDM machining parameters of voltage 75V, electrolyte concentration 20% and tool rotation is 50r/min. The graphical trends show similar results of average MRR was observed previously for silicon wafer and quartz glass materials [7, 14].

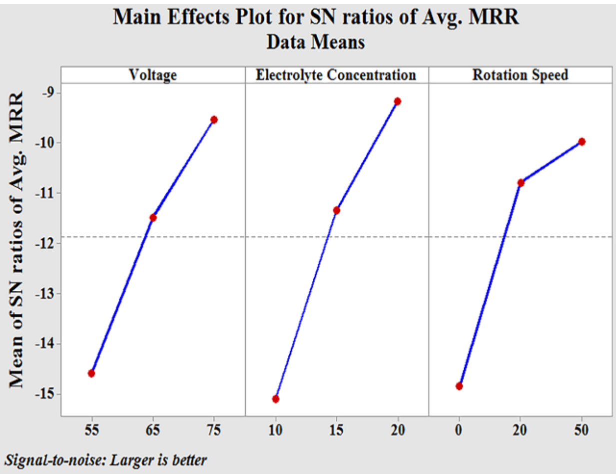


Fig. 4. Main effect plot for average MRR of Soda-lime glass using Copper tool material

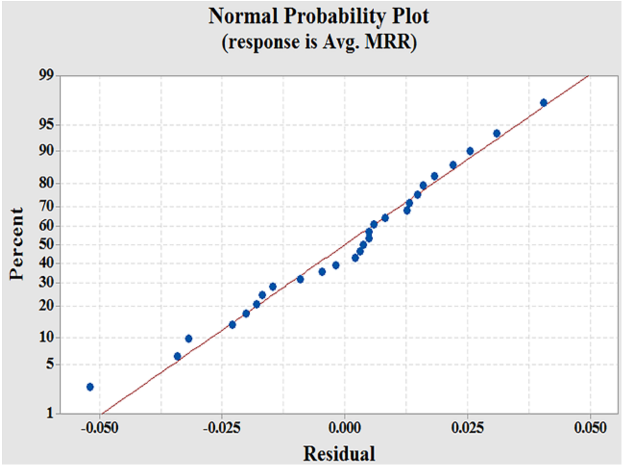
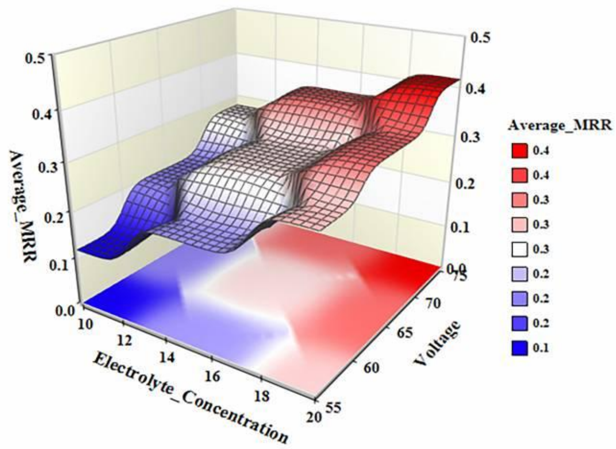
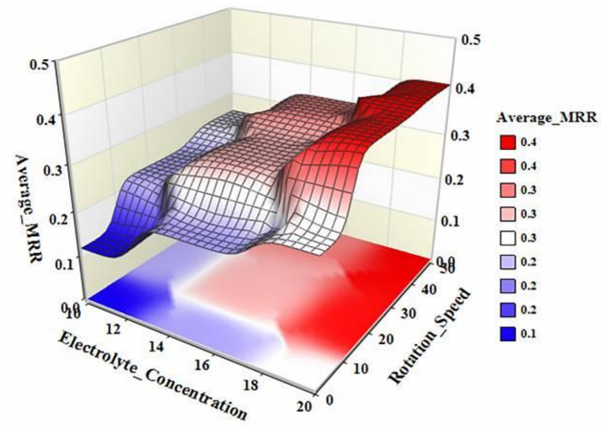


Fig. 5. Normal probability plot for average MRR of Soda-lime glass using Copper tool material

Figure 5 shows that the residuals closely follow the straight line, which means their results, are a good closeness between predicted and experimental obtained values. The graphical analysis of experimental results is carried out by using three-dimensional surface plots. Figure 6 (a)-(c) illustrates the surface plots for average MRR of Soda-lime glass through copper tool material. As seen from the surface graph, it can be concluded that average MRR increases with an increase in electrolyte concentration, voltage and tool rotation. This is because the voltage increases spark energy when it increases, an increase in electrolyte concentration increases the conductivity of the electrolyte and hence it enhances the chemical etching process. The rotation of tool continuous flushing electrolytes which supports to remove eroded material also the sharp tool tip can create the electrical field nearby the tool; hence more material was removed through electrochemical sparks [23, 26]. Figure 6 (a)-(c) elucidates that maximum average MRR spotted on voltage 75V, electrolyte concentration 20% and tool rotation of 50 r/min. Similar results were observed in previous work literature for glass and quartz glass material [7, 8].



(a)



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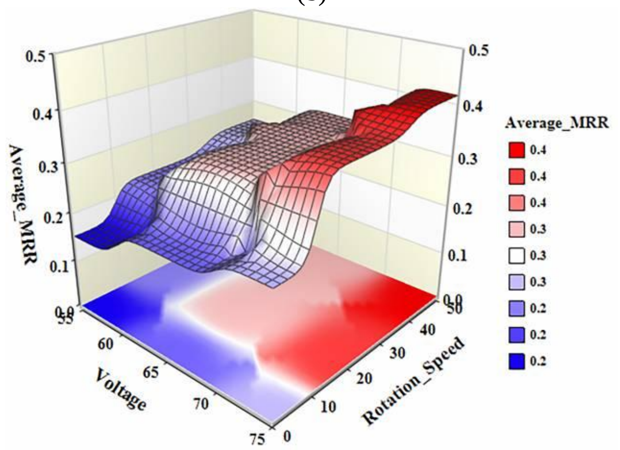


(c)

Fig. 6. 3D surface plot of the average MRR for Soda-lime glass using Copper tool material

The regression model for the average MRR output response of Soda-lime glass machined through copper tool material is shown in equation (4). Whereas, voltage (V), electrolyte concentration (C) and tool rotation (R). The correlation coefficients (R^2) of the average MRR show that 97.56% values are very close to 1. Therefore, it is a significant model as well as the best adequate model.

$$\begin{aligned} \text{Average. MRR} &= -6.15 + 0.0083V \\ &+ 0.0344C + 0.00294R + 0.00003V^2 \\ &+ 0.000156C^2 - 0.000092R^2 + 0.000217V \cdot C \\ &+ 0.000064V \cdot R + 0.000006C \cdot R \end{aligned} \quad (4)$$

3.3 Analysis of average depth of machining for Soda-lime glass material through Copper tool material

Table 7 shows the ANOVA table for an average machined depth of copper tool material in which the condition of larger is better. It indicates that the higher F-value 51.78 was found in the voltage which means it is a very important factor compared to the other two factors. The average machining depth rises with rising voltage from 55 to 75V. The experimental average depths of machining results were very much similar to previously published reports by researchers [23, 26, 27]. Also, all input factors are major effects on machining depth because P values are lower than 0.05. The voltage parameter is 38.02% contributed, electrolyte concentration is contributing 26.60% and tool rotation is 28.03% contributed respectively. Table 8 denotes the responses table for a signal to noise ratios for an average depth of machining. It indicates that voltage is the first rank followed by the concentration of electrolyte and tool rotation.

Table 7. ANOVA table of average machining depth of Soda-lime glass through the Copper tool

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Percentage Contributions
Voltage	2	0.6098	0.3049	51.78	<0.001	38.02
Electrolyte Conc.	2	0.4266	0.2133	36.22	<0.001	26.60
Rotation Speed	2	0.4495	0.2248	38.17	<0.001	28.03
Error	20	0.1178	0.0058			7.35
Total	26	1.6037				100

Table 8. Response table of signal to noise ratios for average machining depth of Soda-lime glass through the Copper tool

Level	Voltage	Electrolyte Concentration	Tool Rotation
1	-13.068	-13.033	-13.027
2	-8.372	-7.862	-6.945
3	-4.756	-5.301	-6.224
Delta	8.312	7.732	6.803
Rank	1	2	3

The main effect plot shown in Figure 7 specifies that the average machining depth, rises considerably with the rise in voltage, the concentration of electrolyte and tool rotation. The higher the average machining depth obtained at ECDM machining parameters of voltage 75V, electrolyte concentration 20% and tool rotation of 50r/min. The similar types of graphical trends were obtained in earlier work of literature for glass materials [8, 23].

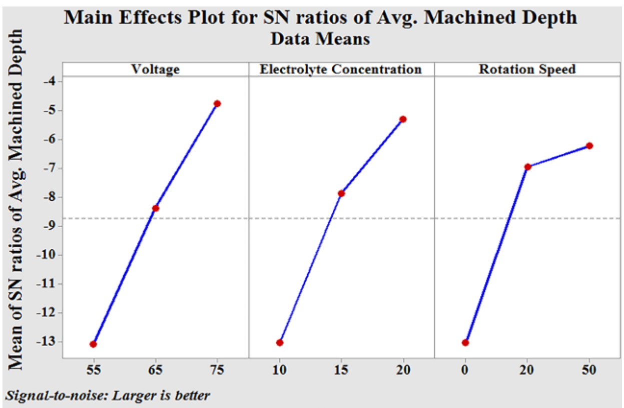


Fig. 7. Main effect plot for average machining depth of Soda-lime glass through the Copper tool material

The histogram for SN ratios of average machining depth is shown in Figure 8 which designates that the residuals are appropriately distributed for all which specifies good agreement of experimental and predicted results for average machining depth. Figure 9 (a)-(c) denotes the 3D surface plots for average machining depth. It shows a greater level of all input factors indicated a maximum average machined depth. Therefore, to achieve a higher average machining depth all parameters to be set at a higher level. Similar graphical results were obtained from previous reports of researchers [23, 26].

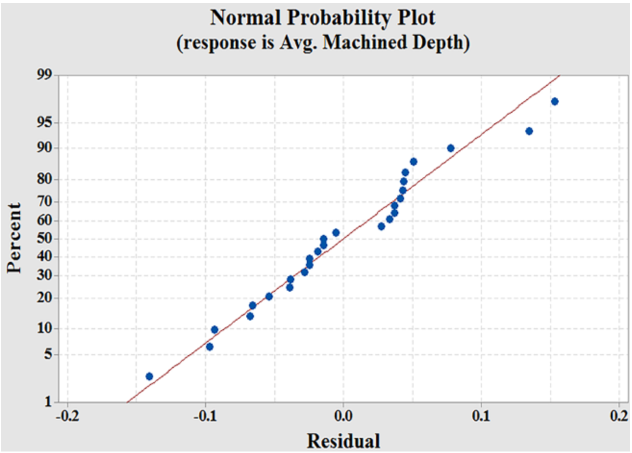
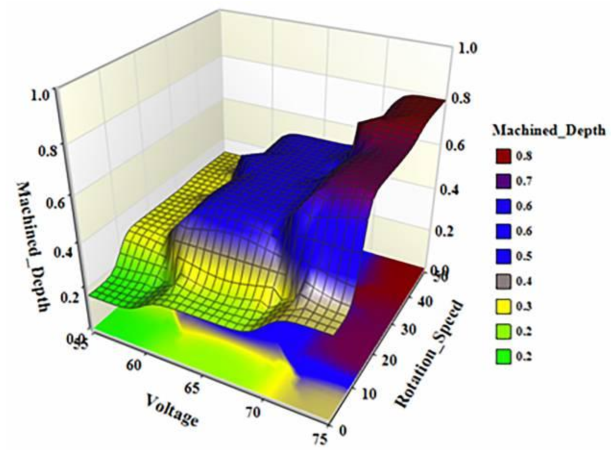
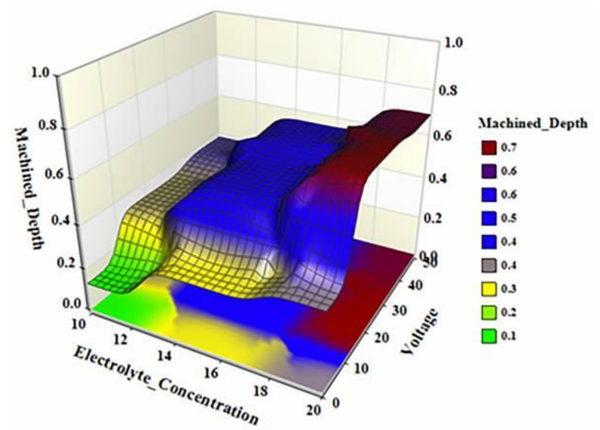


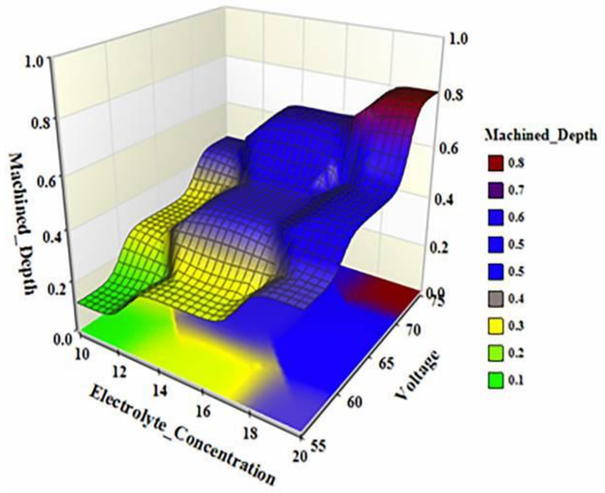
Fig. 8. Normal probability plot for average machining depth of Soda-lime glass through the Copper tool



(a)



(b)



(c)

Fig. 9. 3D surface plot for average machining depth of Soda-lime glass through a Copper tool

The regression model for the average machined depth output response of Soda-lime glass material through the Copper tool is shown in equation (5). The correlation coefficients (R^2) of the average machined depth show that 97.71% values are very close to 1. Therefore, it is the significant model for average machining depth.

$$\text{Average. Machined Depth} = 0.31 - 0.0281V - 0.0312C + 0.00076R + 0.000283V^2 - 0.0070C^2 - 0.000254R^2 + 0.000267V\cdot C + 0.000239V\cdot R + 0.000136C\cdot R \quad (5)$$

3.4 Analysis of average hole diameter of Soda-lime glass through Copper tool material

Table 9 shows the ANOVA table for the average hole diameter of Soda-lime glass through Copper tool material in which the condition of nominal is the best criteria. It indicates that the higher F-value 279.82 was achieved for tool rotation, which means it is the major factor in the other two input factors. The p values indicate that all input factors are lower than 0.05 which means that all parameters are significant. The rotation of the tool electrode is contributing 46.48%, electrolyte concentration is contributing 34.02% and voltage is contributing 17.84%. The results found has a notable agreement with earlier research reports by researchers for radial overcut and hole diameter of glass material [8, 12, 23, 26, 28]. Table 10 shows the response table of the mean of the average hole diameter. It represents that tool rotation is the first rank followed by the concentration of electrolyte and voltage.

The main effect plot is presented in Figure 10 which states that the average hole diameter rises considerably with a rise in the tool rotation speed, electrolyte concentration and voltage linearly.

According to the graph, a higher average hole diameter accomplished at ECDM machining parameters of voltage 75V, the concentration of electrolyte 20% and tool rotation of 50r/min. The identical graphical results were obtained in earlier research works of literature for various types of glass materials [8, 26].

Table 9. ANOVA table for average hole diameter of Soda-lime glass through the Copper tool

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Percentage Contributions
Voltage	2	2.9181	1.4590	107.43	<0.001	17.84
Electrolyte Conc.	2	5.563	2.7813	204.78	<0.001	34.02
Rotation Speed	2	7.6009	3.8004	279.82	<0.001	46.48
Error	20	0.2716	0.0136			1.66
Total	26	16.3532				100

Table 10. Response table for means of nominal is a better criteria of the average hole diameter of Soda-lime glass through the Copper tool

Levels	Voltage	Electrolyte Concentration	Tool Rotation
1	2.479	2.301	2.122
2	2.850	2.902	3.205
3	3.284	3.411	3.286
Delta	0.804	1.111	1.164
Rank	3	2	1

The histogram for SN ratios of average hole diameter is shown in Figure 11 which specifies that the residuals are appropriately distributed for each observed average hole diameter results which indicate the good similarity of experimental and predicted results.

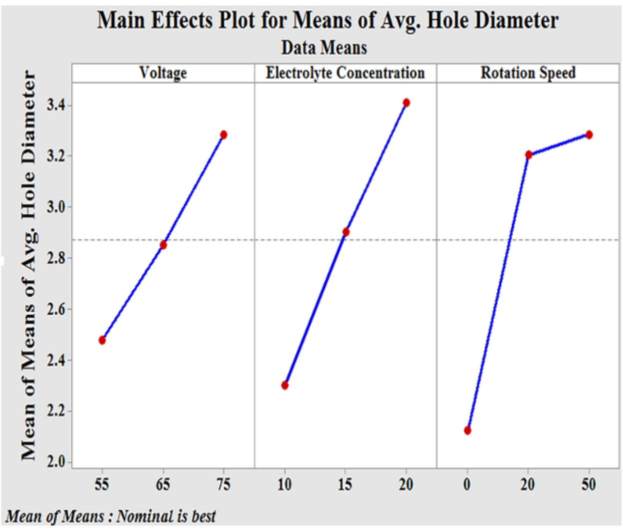


Fig. 10. Main effect plot for average hole diameter of Soda-lime glass through the Copper tool material

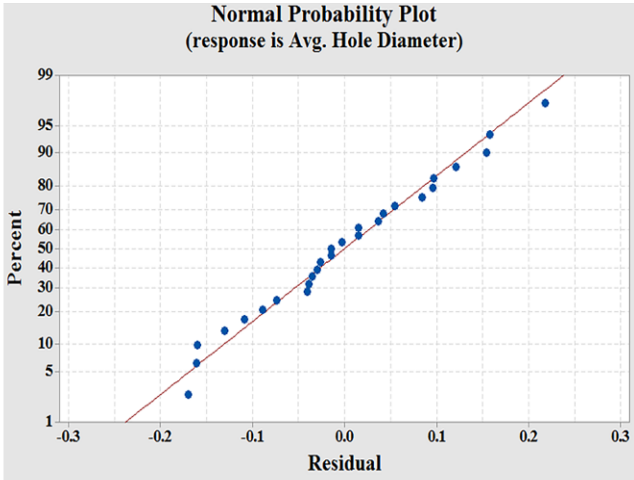
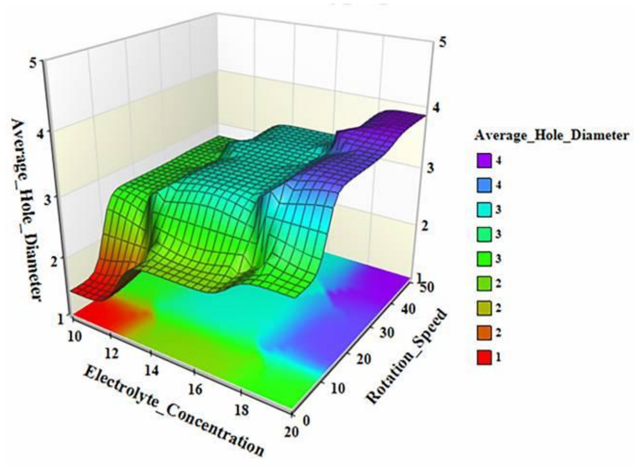
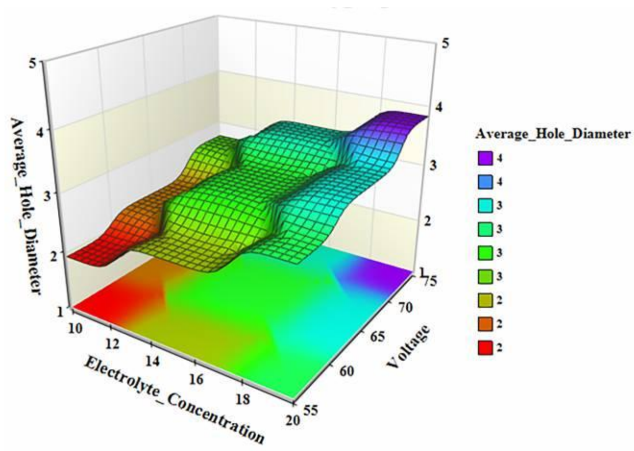


Fig. 11. Normal probability plot of the average hole diameter of Soda-lime glass through the Copper tool

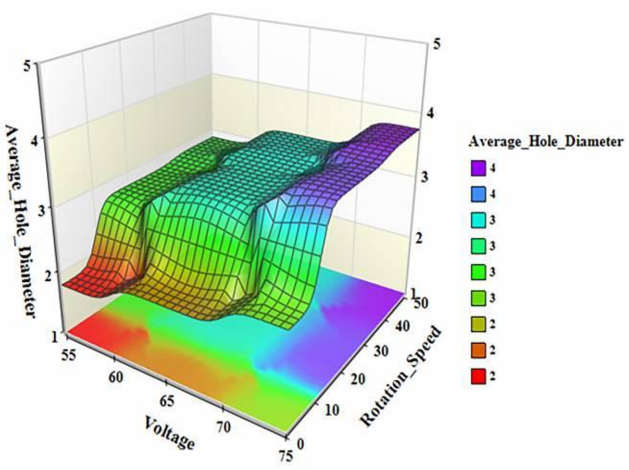
Figure 12 (a)-(c) denotes the 3D surface plots for the average hole diameter of Soda-lime glass through Copper tool material. It represents at a maximum level of each input parameter gives a higher average hole diameter. Therefore, for getting a nominal average hole diameter input machining factors to be set at the optimal level. The same type's graphical results were observed by previous literature [23, 26].



(a)



(b)



(c)

Fig. 12. 3D surface plot of the average hole diameter of Soda-lime glass through the Copper tool material

The regression model of the average hole diameter of Soda-lime glass through the Copper tool is shown in equation (6). The correlation coefficients (R^2) of the average hole diameter indicate that 98.57% values are very close to 1. As a result, it is the best significant model for the average hole diameter.

$$\begin{aligned}\text{Average. Hole Diameter} &= -0.99 - 0.0055V \\ &- 0.1711C + 0.0638R + 0.000317V^2 - 0.00183C^2 \\ &- 0.001029R^2 - 0.000017V\cdot C + 0.000207V\cdot R \\ &- 0.000171C\cdot R\end{aligned} \quad (6)$$

4. VALIDATION OF EXPERIMENTAL RESULTS

The response surface optimization approach has been used to analyze the ECDM input factors for the best output values. The desirability function analysis conditions of maximum average material removal rate, maximum average machined depth, and nominal average hole diameter. The response surface methodology optimization method predicted results were obtained by using Minitab software Soda-lime glass material through the Copper tool is shown in Figure 13. The optimal input factors for desired output are achieved to be at electrolyte concentration 11.21, voltage 75, and rotation speed of 50. Lastly, to check the optimized input factors, an experiment was performed at the same optimal value of ECDM machining parameters which are assessed using the response surface optimization method. The experimental results (Table 11) obtained an average material removal rate of 0.380mg/min, an average machining depth of 0.68mm and an average hole diameter of 3.47. The experimental result makes a difference of 4.22% from its predicted result of average material removal rate, 3.10% for average machined depth and 3.41% of the average hole diameter.

Table 11 shows that the predicted values, experimental values and percentage error between them.

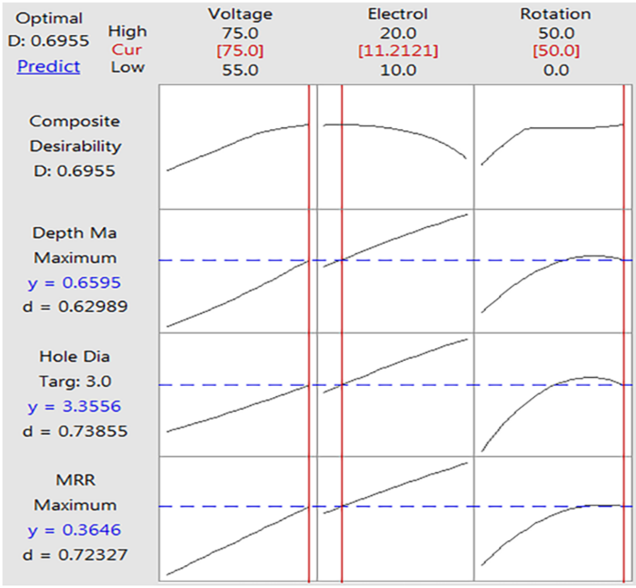


Fig. 13. Response surface methodology optimization plot for average material removal rate, average machined depth, and average hole diameter

Table 11. Confirmation test results and compared to the predicted result

Optimum input factors			Output results	Predicted results	Experimental results	Error (%)
Volt (V)	Conc. (%)	Rotation (r/min)				
75	11.21	50	Average material removal rate (mg/min)	0.3646	0.380	4.22
			Average Machined depth (mm)	0.6595	0.68	3.10
			Average Hole diameter (mm)	3.3556	3.47	3.41

5. CONCLUSIONS

The fabricated electrochemical discharge machine was utilized for the drilling of Soda-lime glass material through Copper tool material. From the present investigation, it is found that the average material removal rate increases with an increase in electrolyte concentration mostly. In the case of average machined depth increases with an increase in voltage mostly. However, for average hole diameter the nominal targeted hole achieved with an increase in the speed of tool rotation. Therefore, for average material removal rate, electrolyte concentration was the most dominating factor, followed by voltage and tool rotation. In the case of average machined depth, the voltage was the major factor, followed by the concentration of electrolyte and tool rotation. Also, for the average hole diameter, tool rotation was the major factor, followed by electrolyte concentration and voltage. The response surface methodology plot shows that the optimum values of input parameters were voltage of 75V, electrolyte concentration of 11.21%, and rotation of 50r/min, to get the higher average material removal rate, maximum average machined depth and targeted nominal average hole diameter.

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