PARAMETRIC ANALYSIS OF ELECTROCHEMICAL DISCHARGE DRILLING ON SODA-LIME GLASS MATERIAL USING TAGUCHI L₂₇ ORTHOGONAL ARRAY METHOD

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Abstract: The Electrochemical discharge machining (ECDM) is a hybrid non-traditional process which is specifically used for machining of conducting as well as non-conducting materials. In this research work, the fabricated ECDM experimental setup was used to machine the Soda-lime glass material with Brass tool material. The experiments were done on Soda-lime glass material with the help of Taguchi L₂₇ orthogonal array method and analysed by using MINITAB 17 software. The average hole diameter and average machined depth results were checked after ECDM drilling on Soda-lime glass material with considering the input process parameters such as an electrolyte concentration, voltage and rotation. The experimental results indicated that voltage was the most dominant factor for average machined depth followed by an electrolyte concentration and rotation speed. The rotation speed was the most dominant factor for average hole diameter followed by voltage and electrolyte concentration.

KEYWORDS: ECDM, Soda-lime Glass, Taguchi, Brass, ANOVA

1 Introduction

Latest mechanical engineering domain needs materials which have properties such as high hardness, light-weight, excellent corrosion resistance, excellent strength to weight ratio, toughness, impact resistance, etc. and these all properties are present in ceramics, composites, alloy materials, glass and hard materials like Tungsten Carbide, Titanium. The machining with these materials is very difficult by using traditional machining methods. Therefore, non-traditional machining methods like electrochemical machining, ultrasonic machining, electrical discharge machine, abrasive jet machining, laser machining, and their hybrid machining processes can be applicable for this machining [1]. The machining of Soda-lime glass material is very difficult and challenging task using traditional machining methods due to its physical properties. It has significant properties such as high electrical resistivity, high hardness, various reflective indices, high brittleness, homogeneity, non-porosity, durability, isotropy, temperature stability, optical transparency, biocompatibility, high chemical and corrosion resistance, and attractive appearance. The Soda-lime glass material is mostly used for the production of mirrors, filters, printed circuit substrates, photographic plates, wafers, photo masks, glass masters, micro-electromechanical systems (MEMS), data storage disks, microscopic slides, touch screens, optical windows, chemical apparatus, camera lens, microfluidic devices, mass spectrometry, micro-capillary electrophoresis and Opto-mechatronic systems [2]. The Soda-lime glass can be cut by using electrochemical discharge machining (ECDM) which is combinations of two machining processes viz. electrochemical machining (ECM) and electro-discharge machining (EDM) [3]. The electrochemical discharge machining technology developed firstly by Kurafuji et al. in the year 1968 [4]. The electrochemical discharge machining (ECDM) is also termed as Discharge machining of non-conductors, Electrochemical Arc Machining, Micro Electrochemical Discharge Machining,

Electro Chemical Spark Machining, and Spark Assisted Chemical Engraving [5]. The maximum precision micro holes were produced by using higher machining voltage and higher electrolyte concentration machining process parameters [6]. The maximum machining depth was attained with the help of abrasive cutting tools in electrochemical discharge drilling process at the maximum electrolyte concentration and supply voltage [7]. In the ECDM process many researchers utilized NaOH as electrolyte medium, Tungsten carbide as cathode tool electrode material and Graphite as anode tool material [8]. In this research report, the developed ECDM setup was used to machine Soda-lime glass material. The average machined depth and average hole diameter were scrutinized with consideration of machining conditions for example voltage, rotation of tool electrode, and electrolyte concentration. The Taguchi L_{27} orthogonal array approach was used for experimentation. The response surface methodology optimization technique was used for machining of Soda-lime glass using Brass tool material.

2 Basic Mechanism of Electrochemical Discharge Machining Process

Figure 1 shows the basic working principle of the ECDM process. In this process cathode, anode and workpiece are immersed inside an aqueous electrolyte medium. The size of the cathode tool is smaller than the anode tool electrode. When D.C. voltage supply approximately around 30 V applied between cathode and anode tool electrode then electrolysis takes place. At that time, oxygen bubbles and Hydrogen gas bubbles are developed at the anode and cathode. When the voltage is increased, then current upsurges and a large amount of bubbles made a bubble layer near the cathode and anode. The bubbles coalesce into a gas film at the nearby surface of the cathode when voltage greatest than the critical voltage. At that moment, the light emission is seeing and electrical discharges take place [5].

Fig. 1 Basic Working Principle of ECDM

3 Fabricated ECDM Setup, Experimental Conditions and Methodology

The ECDM setup was fabricated (figure 2 (a)) and further used to machine Soda-lime glass material using Brass tool material (figure 2 (b)). In this machine X, Y and Z axis movement was controlled by manually. The workpiece was placed on fixture and fixture was situated on ECDM electrolyte cell. The ECDM cell fixed on the X-Y axis compound sliding table which was positioned on the machine table. The cathode electrode was attached to the Z-axis sliding table. The gravity feeding mechanism was used to move the workpiece in an upward direction during the ECDM machining process. The cathode tool electrode was fixed to stepper motor spindle and its speed was operated by Arduino Uno board through the computer. The D.C. voltage was supplied to the cathode tool and an anode tool electrode [9]. The conical taper shaped Brass cathode tool having tip point diameter 1mm and increased up to 3mm diameter was used. The stainless steel 416 was used as the anode electrode having 100 mm length and 15 mm diameter. For the research investigation, NaOH used as electrolyte chemical and

machining time which was fixed to 25 minutes for each experiment. The micro-hole was drilled on $150 \times 140 \times 3 \text{ mm}^3$ Soda-lime glass material plate by using the ECDM process. The Taguchi L_{27} orthogonal array method was applied during the ECDM drilling process. An assortment of the design of experiments concerning the total degree of freedom which was essential for an experiment. In this experimental work three factors was selected with three different levels and their two-way interactions taking into consideration hence, the entire degree of freedom is 18. Therefore, for experimental work L_{27} orthogonal array was utilized, which has 26 degrees of freedom. In this machining process voltage, the rotation speed of tool and electrolyte concentrations were taken as input machining aspect however, average machined depth and average hole diameter were taken as output responses. Table 1 designates the input process parameters and their levels [10].

Fig. 2 (a) Fabricated ECDM Setup for experimentation and (b) Cathode tool electrode (Brass)

Table 1 Process Parameters and Their Levels

Factor	Parameters	Unit	Levels		
			1	2	3
V	Voltage	V	55	65	75
R	Rotation speed	r/min	0	20	50
C	Electrolyte Concentration	%	10	15	20

4 Machining with Fabricated ECDM Setup

The fabricated ECDM setup was used for the machining of Soda-lime glass material with Brass tool material. The sparking intensity was raised when the increase in voltage and electrolyte concentration which causes an increase in average machined depth and average hole diameter. It is observed that when the voltage applied between cathode and anode the bubbles generated because of electrochemically liberated H_2 and water vapour created by ohmic heating at the tool electrode interface. The isolation occurs between the electrode and electrolyte which promotes to discharge as a result of 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 ensue, an avalanche of electrons initiated by ionization flow towards workpiece kept around $20 \mu\text{m}$ distance away from the tooltip. 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 [11-13].

Table 2 shows the sparking intensities of each experiment on Soda-lime glass material using a Brass tool. In this machining process, material removal takes place due to following Eq. 1 or Eq. 2. The glass contains maximum contents of SiO₂ and other components. Similar reactions can occur with the other components of the glass. In this ECDM process when the sodium ion Na⁺ and the hydroxyl ion OH⁻ in the solution adhere to the glass surface, the bond Si–O–Si is broken up and changes into the bond Si–O–Na. Then this reaction diffuses on the surface and the sodium ions impinge other bonds. The bond Na–O is considerably weaker than the siloxane bond Si–O in a glass. Consequently, the surface of the glass is certainly removed. These evidences proposed that the Na⁺ ion helps the glass removal. Furthermore, increasing Na₂O composition makes the surface softer. As a result, the surface will be scraped off with the electrode tip. The etching rate rises noticeably with the temperature and the concentration of hydroxyl anion [6, 14-16].

Figure 3 and 4 shows experimental results of Soda-lime glass material based on Taguchi L₂₇ orthogonal array using Brass tool electrode. The volume of material removal rises with the rise in supply voltage. This is because of a large number of hydrogen bubbles grown at the cathode at the higher value of supply voltage. Similarly, material removal rate increases with increasing electrolyte concentration due to the increase in electrolyte conductivity, it is current drawn capacity increases that evolve higher amount of hydrogen gas bubbles at the cathode and enable improved action of electrical discharge [17]. The tooltip can generate an indent at the starting 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 electrode enhances the roundness of a micro-hole. When electrolysis is localized at the tooltip, most of the bubbles generated at the active tool surface magnificently coalesce into a spherical dielectric gas film. The gas film thickness depends on the geometry of the tool, i.e., the tool radius and exposure length, which is effectively equal to the tool immersing depth. A high tool rotation rate is anticipated to produce chips at a faster rate, thermal softening of glass by sparks seems to be the bottleneck. A high local temperature over 500°C softens the workpiece, making the material easily removed by mechanical micro-drilling. Another possible reason is that the sharp tooltip or edge can exaggerate the electrical field around the tool, thus more material is removed by electrochemical sparks. It is observed that machining depth rises with the rise in applied voltage this is due to field emission law. Since the tool contacts the workpiece, the drilling tool is self-centering as in mechanical micro-drilling process. The hole diameter is a typical parameter to characterize the geometric correctness of ECDM [6, 17-19].

Table 3 shows that micro-holes geometries in different input process variable conditions using a fluorescence optical microscopic. According to it at the 0 r/min conditions the average hole diameter is not perfectly round shape, because of discharge concentrated mostly on the tip of tool electrode and at the round surface of the tool electrode was infrequently, therefore, it is irregular hole geometry. Also, when increasing the voltage and electrolyte concentration then average hole diameters also get increases because of the intensity of spark discharge increases during the ECDM drilling process [17].

Table 2 Sparking intensity during machining of Soda-lime glass by using Brass tool

Brass Tool Electrode Experiments				
Rotation (r/min)			Volt.	Conc.
0	20	50	(V)	(%)
55	10
65
75
55	15
65
75
55	20
65
75

Fig. 3 Experiments on Soda-lime glass material results 1 using Brass tool

Fig. 4 Experiments on Soda-lime glass material replication result 2 using Brass tool

4 Results and Discussion

The design of experiments is an important characteristic to choose the number of experiments. The design of experiments is a structured, planned method for assessing the relationship between factors affecting a process and their output responses. Taguchi method uses an appropriate design of orthogonal arrays to investigate the entire parameters with a small number of experiments. In Taguchi technique, a loss function was used to evaluate the variance between the desired value and the experimental value. Taguchi gives importance to the response variation using the signal to noise (S/N) ratio, which effects in minimizing the quality characteristic variation initiated because of the uncontrollable parameters. The term signal designates the desirable value for output characteristic and noise denotes the undesirable output value. The experiments were based on Taguchi's orthogonal array

Table 3 Microscopic images of Soda-lime glass by using Brass tool for each experiment

Brass Tool Experimental Results 1			Brass Tool Experimental Results 2				
Rotation (r/min)			Rotation (r/min)			Volt. (V)	Conc
0	20	50	0	20	50
55	10
65
75
55	15
65
75
55	20
65
75	

Table 4 Experimental design based on Taguchi L₂₇ orthogonal array and experimental results

Run	Elec.	Voltage	Rotation	Hole	Hole	Avg.	Machined	Machined	Avg.
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	Conc. (%)	(V)	(r/min)	Dia. 1 (mm)	Dia. 2 (mm)	Dia. (mm)	Depth 1 (mm)	Depth 2 (mm)	Depth (mm)
1	10	55	0	1.51	1.58	1.545	0.08	0.06	0.07
2	10	55	20	1.80	2.80	2.3	0.14	0.11	0.125
3	10	55	50	2.50	2.71	2.605	0.13	0.08	0.105
4	10	65	0	1.63	2.12	1.875	0.12	0.10	0.11
5	10	65	20	2.45	2.98	2.715	0.18	0.32	0.25
6	10	65	50	2.80	3.05	2.925	0.22	0.28	0.25
7	10	75	0	2.40	2.41	2.405	0.30	0.27	0.285
8	10	75	20	2.98	3.34	3.16	0.42	0.41	0.415
9	10	75	50	3.08	3.45	3.265	0.66	0.39	0.525
10	15	55	0	1.60	1.63	1.615	0.10	0.09	0.095
11	15	55	20	2.30	3.10	2.7	0.12	0.24	0.18
12	15	55	50	2.37	3.14	2.755	0.15	0.18	0.165
13	15	65	0	1.68	2.58	2.13	0.14	0.14	0.14
14	15	65	20	2.48	3.22	2.85	0.23	0.28	0.255
15	15	65	50	2.41	3.37	2.89	0.34	0.35	0.345
16	15	75	0	1.81	2.83	2.32	0.32	0.27	0.295
17	15	75	20	3.14	3.58	3.36	0.70	0.54	0.62
18	15	75	50	3.20	3.71	3.455	0.79	0.62	0.705
19	20	55	0	2.10	2.41	2.255	0.17	0.23	0.2
20	20	55	20	2.70	3.29	2.995	0.42	0.40	0.41
21	20	55	50	2.62	3.50	3.06	0.37	0.39	0.38
22	20	65	0	2.40	2.52	2.46	0.24	0.25	0.245
23	20	65	20	3.31	3.70	3.505	0.51	0.68	0.595
24	20	65	50	3.38	3.81	3.595	0.55	0.56	0.555
25	20	75	0	2.68	3.12	2.9	0.31	0.38	0.345
26	20	75	20	3.49	4.04	3.765	0.91	1.12	1.015
27	20	75	50	3.71	4.11	3.91	1.02	1.07	1.045

methodology and L_{27} orthogonal array was chosen. Table 4 shows experimental results of input process parameters and output responses. The signal to noise ratio is selected based on the earlier research work information; accordingly, it must be carefully taken S/N ratio is being depended on the nominal-the-better, lower-the-better, larger-the-better criteria. In this research work, the average hole diameter was treated as nominal is best were taken into consideration and the targeted nominal average hole diameter is set for 3.25 mm. In the case of average machining depth larger the better conditions have been selected. The S/N ratio is evaluated by utilizing the following formula which is shown in Eq. 3 and Eq. 4. [20-22].

For larger is better

$$S/N = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right) \quad (3)$$

For nominal is best

$$S/N = 10 \log \left(\frac{\bar{y}^2}{S_y^2} \right) \quad (4)$$

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

4.1 Analysis of average machined depth of Soda-lime using Brass tool material

In this section, the influence of process parameters on average machined depth of Soda-lime glass material using Brass tool material is explained. The ANOVA is used to analyse the significance of input parameters. The response table of signal to noise ratios for average machined depth is larger the better used for ranking of input process parameters. The main effect plot for S/N ratios for average machined depth and three-dimensional surface plots for average machined depth are also explained. The analysis of experimental results which is shown in table 4 was assessed with MINITAB 17 software.

A statistical analysis of variance (ANOVA) was executed to investigate the statistically significant process parameters. The percentage contribution of every process parameter on the total deviation was assessed with the ratio of SS of the equivalent parameter to total SS. The F-value and P-value were used to identify which process has a major effect on output responses [10, 23].

4.1.1 ANOVA for average machined depth

Table 5 shows ANOVA table for the average machined depth of Soda-lime glass material using Brass tool material in which condition of larger is better.

Table 5 ANOVA table for average machined depth of Soda-lime glass material using Brass tool material

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Percentage Contribution
Voltage	2	0.7295	0.36473	30.16	0.000	41.65
Electrolyte Concentration	2	0.4241	0.21206	17.54	0.000	24.21
Rotation Speed	2	0.3561	0.17805	14.72	0.000	20.33
Error	20	0.2418	0.01209			13.81
Total	26	1.7515				100

It shows that the maximum F-value 30.16 was obtained for the voltage which means it is the most dominant factor compared to the other two input parameters. The average machined depth increases with increasing voltage from 55 to 75 V. The increasing trend with voltage is mainly due to field emission law. The observed average machined depth results found out similar trends which were previously published reports by researchers [18, 24, 25]. All input parameters are a significant effect on average machined depth because P values are less than 0.05. The voltage is contributed 41.65%, electrolyte concentration is contributed 24.21% and rotation of tool electrode contributed is 20.33% respectively. Table 6 shows that the response table for the signal to noise ratios of average machined depth using Brass tool material. It shows that voltage is the first rank followed by electrolyte concentration and rotation speed of the tool.

4.1.2 Effect of machining parameters on average machined depth

The main effect plot in figure 5 shows that the average machined depth increases significantly with an increase in voltage, electrolyte concentration and rotation speed of tool electrode. The maximum average machined depth achieved at ECDM machining condition of voltage 75 V, electrolyte concentration 20% and rotation speed of 50 r/min. The similar graphical trends were found out previous literature for glass and Soda-lime glass materials [26, 27].

Table 6 Response table for signal to noise ratios of average machined depth of Soda-lime glass material using Brass tool

Level	Voltage	Electrolyte Concentration	Rotation Speed
1	-15.762	-14.237	-15.193
2	-11.476	-11.886	-8.976
3	-5.629	-6.745	-8.698
Delta	10.132	7.492	6.495
Rank	1	2	3

Fig. 5 Main effect plots for average machined depth of Soda-lime glass using Brass tool

The normal probability plot for the average machined depth of Soda-lime glass using Brass tool is presented in figure 6 which results that the residuals are properly distributed for all observed data of average machined depth. There is no skewness and outliers exist on the graph which shows good agreement of predicted and experimental results.

Figure 6 Normal probability plot for average machined depth of Soda-lime glass using Brass tool material

4.1.3 Analysis of average machined depth using 3D response surface plots

Figure 7 (a-c) represents the 3D response surface plots for the average machined depth of Soda-lime glass material using Brass tool material. It states at a higher level of each input factors which shows maximum average machined depth. Hence for achieving maximum average machined depth the machining parameters to be set at a higher level. Similar graphical trends were observed by previous reports for glass material [18, 25].

Fig. 7 (a-c) 3D response surface plots for average machined depth of Soda-lime glass material using Brass tool

4.2. Analysis of average hole diameter of Soda-lime glass using Brass tool material

The drilling is most important in assembly operation in intricate product manufacturing. Thus, hole making an integral part of the product cycle. The numbers of technological methods have been used to make holes in various products which include conventional and non-conventional machining process [28]. In this research work the effect of machining parameters on the average hole diameter of workpiece material is explained with desirability function is nominal is best to set 3.25 mm targeted value. A similar study was carried out previously regarding the analysis of hole diameter by Chang et al., in which they investigated

characteristics of hole diameter and roundness. They found that the feed rate was the most significant factor affecting the hole diameter and roundness. In this study, the nominal is best criteria for analysing characteristics of hole diameter and roundness [29]. In this section the discussion of statically analysis using ANOVA for average hole diameter using Brass tool material is studied. The response table for means of nominal is better of average hole diameter. The main effect plot, normal probability plot as well as 3D surface plot has also explained for average hole diameter of Soda-lime glass material using Brass tool material.

4.2.1 ANOVA for Average hole diameter

The table 7 shows ANOVA table for average hole diameter of Brass tool material in which condition of nominal is best. It shows that the maximum F-value 333.54 obtained for rotation of tool electrode which means it is the most dominant factor compared to the other two input parameters. This is due to the rotary tool creates self-centering as in mechanical micro-drilling process compared to the stationary tool. The rotation rate produces chips at a faster rate and thermal softening of glass by sparks appears to be the bottleneck which causes improved roundness of hole diameter. The sparks produced around the tool surface during rotary motion, Therefore, rotation of the tool induces a distribution of discharge energy effect. Also, the rotation tool electrode improving the centrifugal ability in the machining gap which improves the insulating ability of the gas bubble layer on the tool electrode surface. Thus, decreases the current density of the process. The rotating speed of the tool electrode improves the heat dissipation capacity in the machining gap [18, 30-33]. The voltage is also the most dominant factor for average hole diameter and then electrolyte concentration. The p values show that all three input parameters are less than 0.05 which are significant. The rotation of tool electrode is contributed 53.44% voltage is contributed 25.28%, and electrolyte concentration is contributed 19.68% respectively. The results obtained has good agreement to already published reports by authors for hole diameter and radial overcut for glass material [6, 7, 18, 25, 30, 34].

Table 7 ANOVA table for average hole diameter of Soda-lime glass using Brass tool

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Percentage Contribution
Voltage	2	2.5056	1.25280	157.83	0.000	25.28
Electrolyte Concentration	2	1.9503	0.97514	122.85	0.000	19.68
Rotation Speed	2	5.2951	2.64756	333.54	0.000	53.44
Error	20	0.1588	0.00794			1.60
Total	26	9.9098				100

Table 8 presents the response table for the mean of average hole diameter for Soda-lime glass material using Brass tool material it shows that rotation speed of the tool is first rank followed by voltage and electrolyte concentration.

4.2.2 Effect of machining parameters on average hole diameter

The main effect plot is shown in figure 8 which specifies the average hole diameter increases significantly with an increase in the rotation speed of tool electrode, voltage, electrolyte concentration linearly. The nominal average hole diameter achieved at ECDM machining condition of voltage 75 V, electrolyte concentration 20% and rotation speed is 50 r/min. The similar graphical trends were found out by previous literature for glass and Soda-lime glass materials [18, 25]. The normal probability plot of average hole diameter is

presented in figure 9 which indicates that the residuals are properly distributed for all results data which means it is the good agreement of predicted and experimental results.

Table 8 Response table of means for average hole diameter of Soda-lime glass using Brass tool material

Level	Voltage	Electrolyte Concentration	Rotation Speed
1	2.426	2.533	2.167
2	2.772	2.675	3.039
3	3.171	3.161	3.162
Delta	0.746	0.628	0.995
Rank	2	3	1

Fig. 8 Main effect plot for average hole diameter of Soda-lime glass using Brass tool material

Fig. 9 Normal Probability plot for average hole diameter of Soda-lime glass using Brass tool material

4.2.3 Analysis of average hole diameter using 3D response surface plots

Figure 10 (a)-(c) represents the 3D response surface plots for the average hole diameter of Soda-lime glass material using Brass tool material. It states that at a higher level of each input factors shows increasing average hole diameter. Hence for achieving nominal average hole diameter, machining parameters to be set at the optimal level. Similar trends were observed by Wei et al. and Razfar et al. [18, 25].

Fig. 10 (a-c) 3D response surface plot for average hole diameter of Soda-lime glass material using Brass tool material

4.3 Development of mathematical modeling for Soda-lime glass material using Brass tool material

The mathematical modeling is developed by using Minitab 17 software in the form linear regression model which is used for the optimization of the output responses. The predicted model validation was test through the P-value with 95% confidence level. The R^2 values, in this case, are high and close to 1, which is desired for evidencing the high significance of the model and the best fit for the model [35]. The regression model for Brass tool material output responses of Soda-lime glass material using responses surface methodology is shown in Eq. 5 and Eq. 6. The correlation coefficients (R^2) of average

machined depth and average hole diameter shows that 94.68%, and 98.41% which are exact close to 1. Therefore, it is the desired significance model and the best fit for the model.

Average Machined Depth

$$= 4.01 - 0.1082V - 0.1228C - 0.01318R + 0.000828V^2 + 0.00294C^2 - 0.000216R^2 + 0.000817V * C + 0.000340V * R + 0.000464C * R \quad (5)$$

R ²	R ² (adj.)
94.68%	91.87%

Average hole diameter

$$= 1.14 + 0.0056V - 0.1298C + 0.06021R + 0.000267V^2 + 0.00687C^2 - 0.000789R^2 - 0.000192V * C - 0.000004V * R - 0.00004C * R \quad (6)$$

R ²	R ² (adj.)
98.41%	97.57%

5 Optimization of experimental result

The final stage of the experimental study is to find optimal machining parameters to achieve the desired machined responses such as average machining depth and average hole diameter for electrochemical discharge machining of Soda-lime glass material using Brass tool material. To accomplish the desired target, the desirability function analysis of response surface optimization is the most effective technique used to determine the appropriate machining parameters in electrochemical discharge machining. Figure 11 shows the optimization plot for the responses of Soda-lime glass material using a Brass tool in electrochemical discharge machining process. From the figure, the optimal machining process parameters are found to accomplish the desired goals.

Fig. 11 Optimization plot for output responses of Soda-lime glass using Brass tool

6 Confirmation test

After the selection of optimal level of the machining process parameters, the last step is to predict and validate the improvement of the output responses with optimal level of the machining parameters. The response surface methodology optimization approach predicted results with Minitab software for machining of Soda-lime glass workpiece material using the

Brass tool. The response surface methodology approach has been employed to scrutinize the ECEDM machining parameters for the best response values. The optimal machining parameters for desired responses are found to be at voltage 75, electrolyte concentration 20 and rotation speed of 6.15. Finally, to validate the optimized parameter, an experiment was executed at the same optimal value. The experimental results were found to be the average machined depth of 0.61 mm and the average hole diameter of 3.32 mm. The experimental value makes a difference of 2.49 % from its predicted value for average machining depth and 2.10 % for average hole diameter. It shows that the overall performance of the ECEDM process for Soda-lime glass material has been improved which is presented in table 9.

Table 9 Confirmation test results and comparison with predicted result

Optimum parameters			Output results	Predicted results	Experimental results (mm)	Error (%)
Volt (V)	Conc. (%)	Rotation (r/min)				
75	20	6.15	Average machined depth (mm)	0.6256	0.61	2.49
			Average hole diameter (mm)	3.25	3.32	2.10

CONCLUSION

The fabricated ECEDM setup was used for the machining of Soda-lime glass material using Brass tool material. In this work, two output responses are investigated viz. average machined depth and average hole diameter by considering the three input factors such as voltage, electrolyte concentration, and rotation speed. From present experimental observations, it can be concluded that voltage was the most significant factor for the average machined depth and followed by electrolyte concentration and rotation speed. In case of average hole diameter, rotation speed was the most influencing parameter and followed by voltage and electrolyte concentration. The optimum input factors combination for maximum average machined depth and the nominal value for average hole diameter are voltage 75 V, electrolyte concentration 20 %, and rotation 6.15 r/min.

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