JOURNAL OF ENGINEERING SCIENCES
ЖУРНАЛ ІНЖЕНЕРНИХ НАУК
ЖУРНАЛ ИНЖЕНЕРНЫХ НАУК
Web site: http://jes.sumdu.edu.ua
DOI: 10.21272/jes.2019.6(2).f1
Volume 6, Issue 2 (2019)

Analysis of Machined Depth and Hole Diameter on Soda-lime Glass Using Electrochemical Discharge Machining Process

Pawar P.*, Kumar A., Ballav R.

National Institute of Technology Jamshedpur, 831014 Jamshedpur, Jharkhand, India

Article info:
Paper received: February 19, 2019
The final version of the paper received: April 6, 2019
Paper accepted online: April 11, 2019

***Corresponding Author's Address:**
pravin.1900@gmail.com

Abstract. The machining of a glass material is highly complicated due to its physical as well as chemical properties. The electrochemical discharge machining is an integrated hybrid machining process which has utilized to machining of conducting materials as well as high strength non-conducting materials having brittleness and high hardness. In this research article, the electrochemical discharge machining experimental setup was built and fabricated for machining of non-conducting materials. The electrochemical discharge machining process was applied for drilling on soda-lime glass material. The experiments were done with reference to Taguchi L_{27} orthogonal array approach and scrutinized by utilizing the MINITAB 17 software. The machined depth and hole diameter results were inspected after electrochemical discharge drilling on soda-lime glass material with considering the machining conditions such as voltage, electrolyte concentration, and rotation. The observation results showed that voltage is the major parameter for machined depth and hole diameter followed by electrolyte concentration and rotation of tool electrode.

Keywords: electrochemical discharge machining, machined depth, hole diameter, Taguchi method, soda-lime glass.

1 Introduction

The machining technology is utilized to make the high-quality product by changing shape, tolerance, dimensions and surface quality of the product. The advanced non-traditional technique is employed for machining of hard and brittle materials [1]. The electrochemical discharge machining (ECDM) technique is combinations of two manufacturing process viz. electrochemical machining process (ECM) and electro-discharge machining (EDM) process [2]. The ECDM process is beneficial to machined non-conducting materials by combined machining effect i.e. electric discharge and electrochemical reaction process [3]. The ECDM machining technology invented firstly by Kurafuji et al. in the year 1968 [4]. In this process at higher machining voltage and higher electrolyte concentration machining conditions can produce micro holes with maximum precision [5]. The maximum machining depth was achieved by using abrasive cutting tools in the ECDM drilling process at the highest electrolyte concentration and supply voltage [6]. In ECDM process the mean stationary current-voltage characteristics have mainly five notable regions such as instability region, thermodynamic and over the potential region, Ohmic region, arc region and limiting current region [7]. In the area of ECDM process, the many researchers utilized NaOH as electrolyte medium, Tungsten carbide as cathode tool electrode material and Graphite as anode tool material [8]. The glass is the most important material for engineering and medical field from the very long period because of vast development in the glass industry. It has very important properties such as high electrical resistivity, various reflective indices, homogeneity, high hardness, non-porosity, durability, isotropy, temperature stability, high chemical and corrosion resistance, attractive appearance, optical transparency and biocompatibility [9].

In this research work the ECDM was designed and fabricated which was used to machined soda-lime glass material. The machined depth and hole diameter were investigated with consideration of machining conditions such as voltage, rotation of tool electrode, and electrolyte concentration.

2 Research Methodology

2.1 Basic working principle and experimental setup of ECDM

Figure 1 represents the basic working principle of the ECDM process. In this process, a 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 approx. 20 to 30 V applied between cathode and anode tool electrode then electrolysis takes place. Then, oxygen bubbles and Hydrogen gas bubbles are developed at the anode and cathode. When the voltage is raised, the current rises and a large number of bubbles formed a bubble layer around the cathode and anode. The bubbles coalesce into a gas film at the round surface of the cathode when voltage utmost than the critical voltage. At that time the light emission is seeing and electrical discharges take place. The fabricated ECDM machining setup is shown in Figure 2.

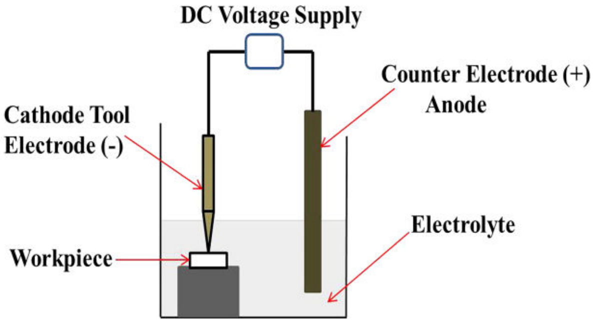

Figure 1 – Basic working principle of ECDM

Figure 2 – Experimental setup of ECDM

2.2 Experimental conditions

In this setup X, Y and Z axis movement was controlled by manually using compound sliding (X and Y) and single axis sliding (Z) mechanism. The workpiece was holding on fixture and fixture was placed on ECDM electrolyte cell. The ECDM cell fixed on the X-Y axis compound slide which was mounting on the machine table. The cathode electrode was attached to the Z-axis sliding table. The gravity feeding mechanism was used to move workpiece in the upward direction during the ECDM machining process. The cathode tool electrode was fixed to stepper motor spindle and its speed is controlled with Arduino Uno board through the computer. The D.C. voltage was given between the cathode tool and the anode tool electrode [10]. The conically shaped cathode electrode (gunmetal) having tooltip diameter 1 mm and increased up to 3 mm diameter was utilized. The stainless steel 416 was taken as the anode electrode having 15 mm diameter. For the experimentation, KOH electrolyte chemical was used and machining time is set to be 15 minutes for each experiment. The micro-hole was drilled on 150×140×3 mm^3 Soda-lime glass material plate by using the ECDM process. The Taguchi L_{27} orthogonal array method was applied during ECDM drilling. An assortment of the design of experiments with reference to the total degree of freedom required for an experiment. In this experimental work selecting, three factors with three levels and their two-way interactions taking into consideration thus. The total degree of freedom is 18. Therefore, for experimental work L_{27}, an orthogonal array was utilized, which has 26 degrees of freedom. In this machining process voltage, rotation and electrolyte concentrations were taken as input machining factors with machined depth and hole diameter were taken as output responses. Table 1 indicates that input process parameters and their individual levels [11].

Table 1 – Process parameters and their levels

Factor	Parameters	Unit	Levels		
			1	2	3
V	Voltage	V	45	55	65
R	Rotation speed	rpm	15	30	50
C	Electrolyte Concentration	%	05	10	15

The Table 2 shows that experimental results which include input process parameters and output responses. The signal indicates the influence of each factor on the response, while noise is the measure of the effect of deviation as of average responses. S/N ratio is being contingent on the nominal-the-better, lower-the-better, larger-the-better criteria. The S/N ratio is selected based on the previous research work information and expertise. In current experimental work, hole diameter was considered as nominal is best because average hole diameter results were taken into consideration and the targeted nominal hole diameter is set for 2 mm. In the case of machined depth larger-the-better criteria has been chosen. The S/N ratio is evaluated by utilizing the following formula shown in equations [12]:

1) for larger is better:

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

2) for nominal is the best:

$$S/N = -10\log_{10}\left(\sigma^2\right) \tag{2}$$

where σ – standard deviation of the responses for all noise factors for the given factor level combination. The analysis of experimental results which is shown in Table 2 was estimated with the MINITAB 17 software.

Microscopic images of experimental results are presented in Figure 3.

Table 2 – Taguchi L_{27} Orthogonal array and experimental results

No.	Voltage, V	Rotation speed, rpm	Electrolyte concentration, %	Hole diameter, mm	Machined depth, mm
1	45	15	05	0.70	0.05
2	45	15	10	1.06	0.08
3	45	15	15	1.20	0.10
4	45	30	05	1.02	0.07
5	45	30	10	1.13	0.08
6	45	30	15	1.18	0.10
7	45	50	05	1.15	0.08
8	45	50	10	1.21	0.11
9	45	50	15	1.28	0.10
10	55	15	05	1.52	0.09
11	55	15	10	1.58	0.13
12	55	15	15	1.70	0.18
13	55	30	05	1.50	0.11
14	55	30	10	1.62	0.14
15	55	30	15	1.75	0.19
16	55	50	05	1.55	0.12
17	55	50	10	1.60	0.16
18	55	50	15	1.74	0.20
19	65	15	05	1.64	0.15
20	65	15	10	1.81	0.17
21	65	15	15	1.92	0.24
22	65	30	05	1.61	0.14
23	65	30	10	1.77	0.26
24	65	30	15	1.95	0.25
25	65	50	05	1.58	0.17
26	65	50	10	1.88	0.28
27	65	50	15	2.02	0.32

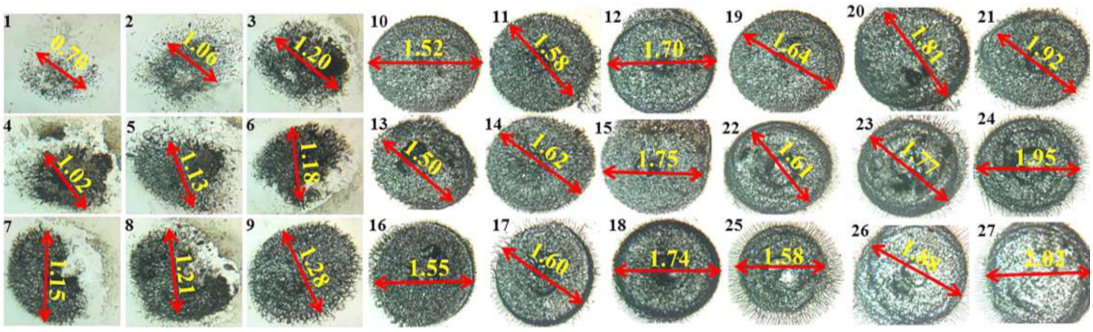

Figure 3 – Microscopic images of experimental results

3 Results and Discussion

3.1 Effect on the machined depth

The rotary speed of tool electrode may possibly influence the efficiency, cutting ability and quality of machining performance [13, 14].

The voltage has utmost significant parameters during the ECDM drilling process because it creates more sparks energy when the voltage is increased. Consequently, it increases the machined depth when increasing voltage. Also, high electrolyte concentration raises chemical etching of glass which rises machining depth [7]. In this study, the machining depth is raised when the applied voltage rises from 45 to 65 V. This is due to the applied voltage is primarily because of field emission law [13, 18].

Figure 4 shows the mean S/N ratios plot for machined depth which indicates the effect of each parameter on machined depth. Figures 5–7 show surface plots for machined depth which indicates the influence of three different parameters viz. voltage, rotation and electrolyte concentration on the machined depth output response. The following figures exhibit the linear increase in voltage resulting in the increase in machined depth hence it is the major parameter.

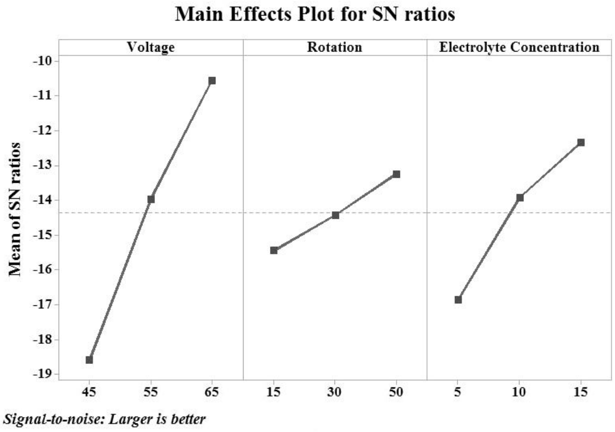

Figure 4 – Mean S/N ratios plot for machined depth

The mathematical model for machined depth was getting through the MINITAB 17 software which is presented as follows:

$$Machined..Depth = 0.179 + (1.60V^2 + 0.04R^2 + 0.36C^2 - 6.42V - 0.30R - 8.68C)\cdot 10^{-3} + (41.70VC + 2.10RC - 7.10VR)\cdot 10^{-5}. \quad (3)$$

The ANOVA table (Table 3) shows the P-value of voltage, the concentration of electrolyte and rotation is smaller than 0.05 therefore, is it most significant parameters. The value of R-squared is 90.2 %. The Pred. R-squared of 82.1 % is in reasonably similar to the Adj. R-squared of 87.2 %. The response table 4 reveals the average of each output response characteristic for each level of each factor. The ranks and delta values showed that voltage has the maximum effect on machined depth and is followed by electrolyte concentration and rotation.

Table 3 – ANOVA table for machined depth

Source	DF	Adj SS	Adj MS	F value	P value
Voltage	2	0.0816	0.0408	64.35	0.000
Electrolyte conc.	2	0.0277	0.0135	21.85	0.000
Rotation	2	0.0069	0.0034	5.41	0.013
Error	20	0.0127	0.0006	–	–
Total	26	0.1288	–	–	–
S		R-sq.	R-sq. (adj.)	R-sq. (pred.)	
0.025		90.2 %	87.2 %	82.1 %	

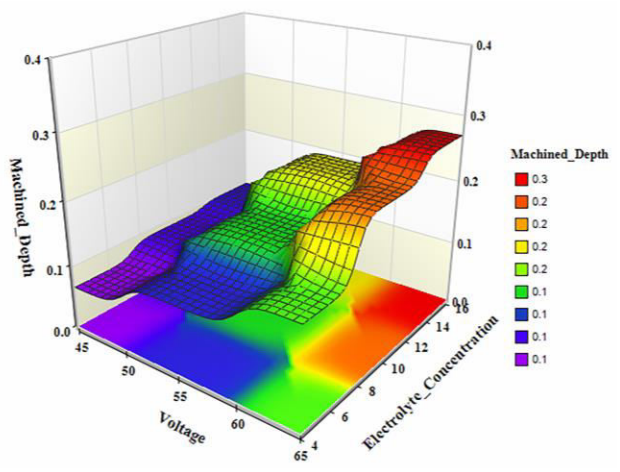

Figure 5 – Surface plot for machined depth vs. voltage, electrolyte concentration

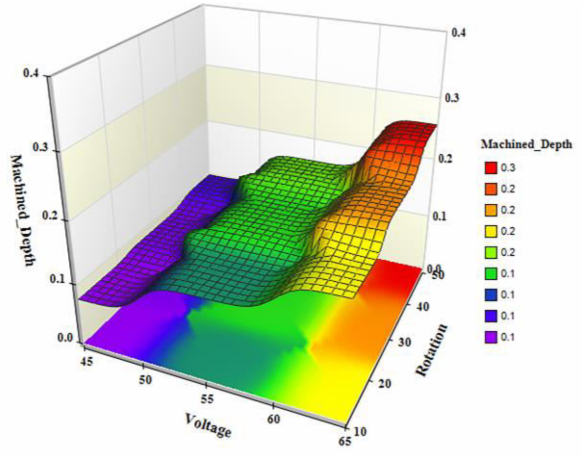

Figure 6 – Surface plot for machined depth vs. voltage, rotation

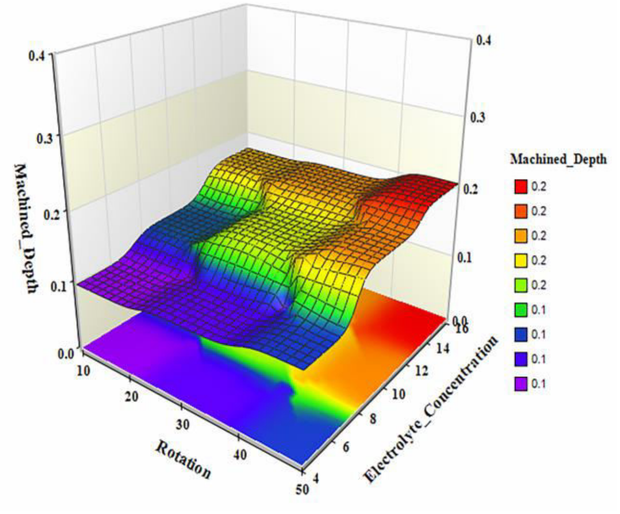

Figure 7 – Surface plot for machined depth vs. rotation, electrolyte concentration

Table 4 – Response table for S/N ratios of machined depth

Level	Voltage, V	Electrolyte concentration, %	Rotation, rpm
1	–21.6	–19.8	–18.4
2	–17.0	–16.9	–17.4
3	–13.5	–15.3	–16.2
Delta	8.1	4.5	2.2
Rank	1	2	3

3.2 Effect on hole diameter

When voltage and electrolyte concentration raises then hole diameter also rises. Thus, voltage and electrolyte concentration are the utmost important parameters for hole diameter during ECDM drilling process [15, 16]. Figure 8 shows the mean plot for hole diameter during ECDM soda-lime glass drilling process which indicates the effect of each parameter on hole diameter.

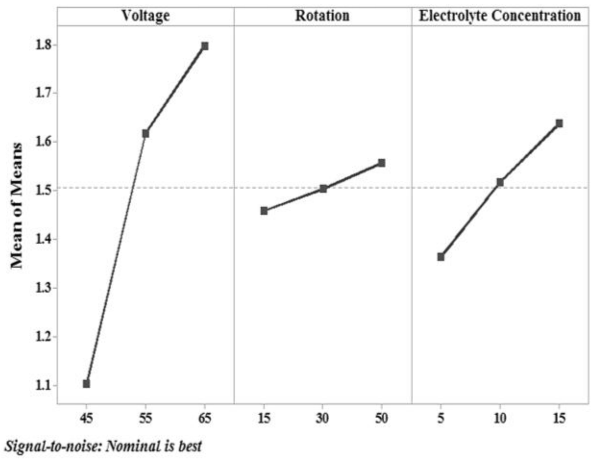

Figure 8 – Mean plot for hole diameter

Figures 9–11 show surface plots for hole diameter which indicates the influence of three different parameters viz. voltage, rotation and electrolyte concentration on the hole diameter output response. The figure exhibits the linear increase in voltage subsequent into linearly increases in hole diameter, as a result, it is the major parameter.

ANOVA indicated that the total sum of squares of the deviation is the same as the sum of the square of standard deviation initiated by each input factor which is shown in table 5 for hole diameter. The statistical consequence to the output response is calculated by using the F-values and P-values of ANOVA. If the P-value is lesser than 0.05 then the parameter is significant. The highest value F shows the most significant parameter. The R-squared is statistical measures of the intimacy of the data are to fit the regression line. In this experimental study, attained the value of R-squared is 95.78%. The Pred. R-squared of 92.30% is in reasonably similar with the Adj. R-squared of 94.51%.

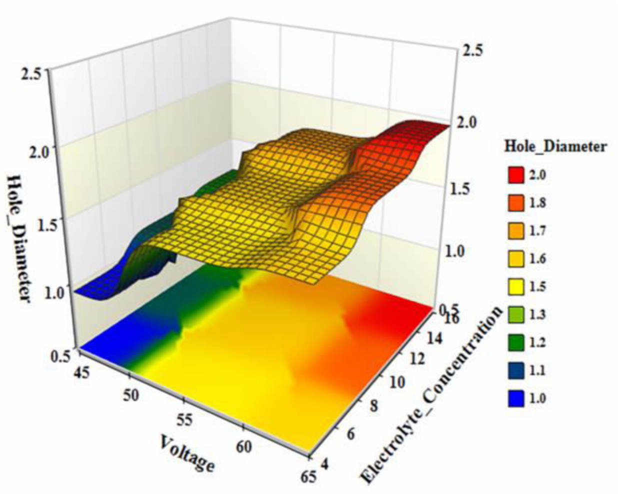

Figure 9 – Surface plot for hole diameter vs. voltage, electrolyte concentration

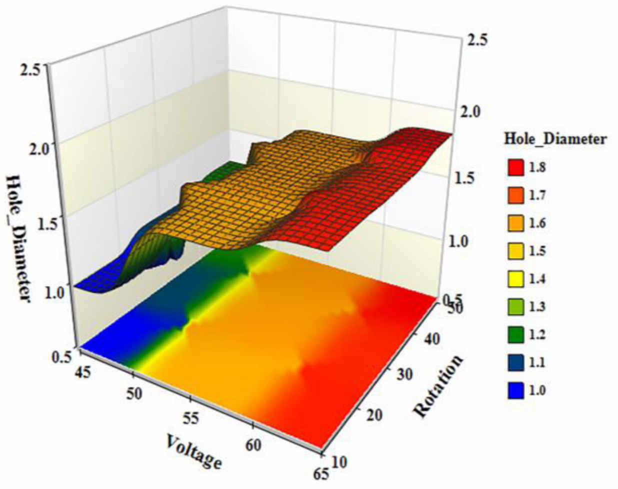

Figure 10 – Surface plot for hole diameter vs. voltage, rotation

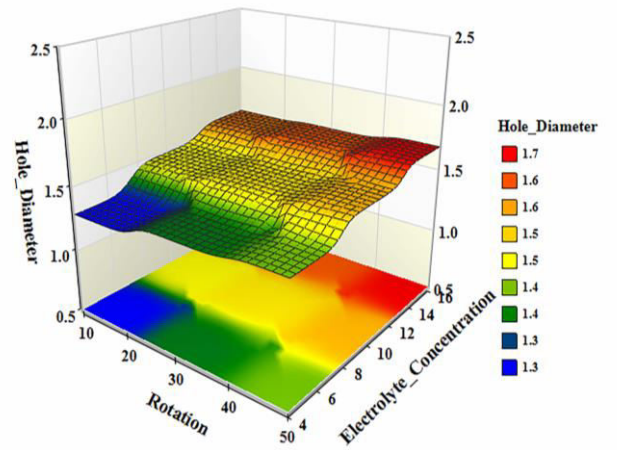

Figure 11 – Surface plot for hole diameter vs. rotation, electrolyte concentration

The F value is highest for the parameter of voltage therefore, it is the most significant parameter. The P value of voltage and electrolyte concentration is lower than 0.05 as a result, it is most dominant parameters [17]. The response Table 6 demonstrates the average of each output response characteristic for each level of each factor. The ranks and delta values showed that voltage has the highest influence on hole diameter and is followed by electrolyte concentration and rotation.

Table 5 – ANOVA table for hole diameter

Source	DF	Adj SS	Adj MS	F value	P value
Voltage	2	2.3379	1.1690	194.80	0.000
Electro-lyte conc.	2	0.3407	0.1704	28.38	0.000
Rotation	2	0.0431	0.0216	3.59	0.046
Error	20	0.1201	0.0060	–	–
Total	26	2.8418	–	–	–
S		R-sq.	R-sq. (adj.)	R-sq. (pred.)	
0.077		95.8 %	94.5 %	92.3 %	

Table 6 – Response table for hole diameter

Level	Voltage, V	Electrolyte concentration, %	Rotation, rpm
1	1.1	1.4	1.4
2	1.6	1.5	1.5
3	1.8	1.6	1.6
Delta	0.7	0.3	0.1
Rank	1	2	3

The mathematical model for hole diameter was getting through the MINITAB 17 software which is presented as follows:

$$Hole.Diameter = -6.047 + 0.2225V + 0.01965R + \\ + 0.0221C - 0.001672V^2 + 0.00008R^2 - 0.0069C^2 - \\ - 0.00264VR + 0.000450VC - 0.000179RC. \quad (4)$$

3.3 Confirmation tests

Confirmation test has been carried out to validate the enhancement of performance characteristics while ECDM of soda-lime glass material. The optimum parameters are selected for the confirmation test from response surface methodology optimization graph which is shown in Figure 12. It can be seen that the overall performance of the ECDM process for soda-lime glass material has been improved which is shown in Table 7.

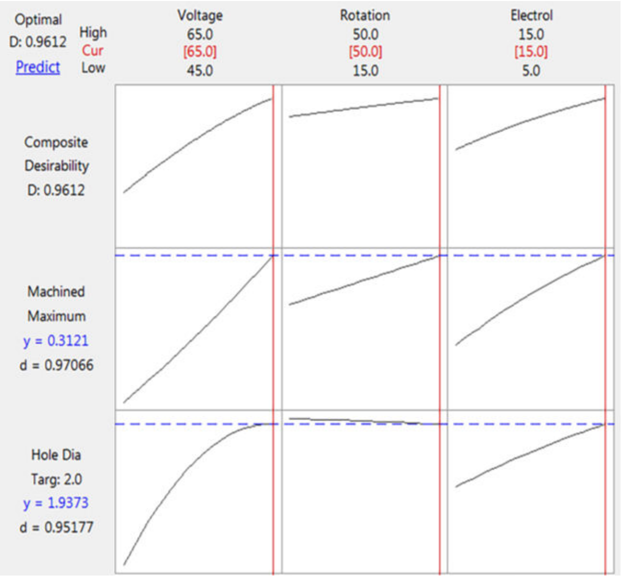

Figure 12 – Response surface methodology optimization plot for machined depth and hole diameter

Table 7 – Confirmation test results

Optimal parameters			Output results	Predicted results	Exper. res.	Error, %
Volt.	Conc.	Rot.				
65	15	50	Machined depth, mm	0.31	0.29	7.6
			Hole diameter, mm	1.94	2.05	5.8

4 Conclusions

The ECDM setup was built, design and manufactured for machining of non-conducting materials. In this work, two output responses are investigated viz. machined depth and hole diameter by considering the three input factors such as voltage, electrolyte concentration, and rotation. The experimental work was carried out using the ECDM process on soda-lime glass material using gun-metal as a cathode electrode. From the current experimental observations, it can be concluded that the voltage was the most significant factor for the machined depth and hole diameter followed by electrolyte concentration and rotation. The optimum input factors combination for maximum machined depth and the nominal value for hole diameter are voltage 65 V, electrolyte concentration 15 %, and rotation 50 rpm.

References

1. Slatineanu, L., Dodun, O., Coteata, M., Goncalves-Coelho, A.M., Besliu, I., Pop, N. (2009). Machining methods based on the impact effects. *International Journal of Modern Manufacturing Technologies*, Vol. 1(1), pp. 83–88.
2. Goud, M., Sharma, A. K., Jawalkar, C. (2016). A review on material removal mechanism in electrochemical discharge machining (ECDM) and possibilities to enhance the material removal rate. *Precision Engineering*, Vol. 45, pp. 1–17.
3. Singh, T., Dvivedi, A. (2016). *Developments in electrochemical discharge machining: A review on electrochemical discharge machining, process variants and their hybrid methods. International Journal of Machine Tools and Manufacture*, Vol. 105, pp. 1–13.

4. Kurafuji, H., Suda, K. (1968). Electrical discharge drilling of glass, *Annals of the CIRP*, Vol. 16, pp. 415–419.
5. Yang, C. T., Ho, S. S., Yan, B. H. (2001). Micro hole machining of borosilicate glass through electrochemical discharge machining (ECDM). *Key Engineering Materials*, Vol. 196, pp. 149–166.
6. Jain, V. K., Choudhury, S. K., Ramesh, K. M. (2002). On the machining of alumina and glass, *International Journal of Machine Tools and Manufacture*, Vol. 42(11), pp. 1269–1276.
7. Wuthrich, R., Fascio, V. (2005). Machining of non-conducting materials using electrochemical discharge phenomenon – an overview. *International Journal of Machine Tools and Manufacture*, Vol. 45(9), pp. 1095–1108.
8. Pawar, P., Ballav, R., Kumar, A. (2015). Revolutionary developments in ECDM process: an overview. *Materials Today: Proceedings*, Vol. 2(4–5), pp. 3188–3195.
9. Bansal, N. P., Doremus, R. H., (2013). Handbook of Glass Properties (1st ed.). *Elsevier Publishing*.
10. Pawar, P., Ballav, R., Kumar, A. (2018). *Development and manufacturing of Arduino based electrochemical discharge machine*, *Journal of Machine Engineering*, Vol. 18(1), pp. 45–60.
11. Pinar, A. M., Uluer, O., Kırmaci, V. (2009). Optimization of counter flow Ranque–Hilsch vortex tube performance using Taguchi method. *International Journal of Refrigeration*, Vol. 32(6), pp. 1487–1494.
12. Roy, A., Nath, N., Nedelcu, D. (2017). Experimental investigation on variation of output responses of as cast TiNiCu shape memory alloys using wire EDM. *International Journal of Modern Manufacturing Technologies*, Vol. 9(1), pp. 90–101.
13. Jiang, B., Lan, S., Ni, J. (2014). Experimental investigation of drilling incorporated electrochemical discharge machining. *Proceedings of the ASME 2014 International Manufacturing Science and Engineering Conference*, Vol. 2, pp. 1–8.
14. Chak, S. K., Rao P. V. (2008). The drilling of Al_2O_3 using a pulsed DC supply with a rotary abrasive electrode by the electrochemical discharge process. *The International Journal of Advanced Manufacturing Technology*, Vol. 39(7–8), pp. 633–641.
15. Mallick. B., Sarkar. B. R., Doloi. B., Bhattacharyya. B. (2014). Multi criteria optimization of Electrochemical Discharge Micromachining process during micro-channel generation on glass. *Applied Mechanics and Materials*, Vol. 592–594, pp. 525–529.
16. Madhavi, B. J., Hiremath, S. S. (2016). Investigation on machining of holes and channels on borosilicate and sodalime glass using μ-ECDM Setup. *Procedia Technology*, Vol. 25, pp. 1257–1264.
17. Greenland, S., Senn, S. J., Rothman, K. J., Carlin, J. B., Poole, C., Goodman, S. N., Altman, D. G. (2016). Statistical tests, P values, confidence intervals, and power: a guide to misinterpretations. *European Journal of Epidemiology*, 3Vol. 1(4), pp.337–350.
18. Wei C., Ni J., Hu, D. (2010). Electrochemical discharge machining using micro-drilling tools. *Transactions of NAMRI/SME*, Vol. 38, pp. 105–111.

УДК 621.793

Аналіз глибини і діаметра отворів при електрохімічному обробленні силікатного скла

Павар П., Кумар А., Баллав Р.

Національний технологічний інститут м. Джамшедпур, 831014,м. Джамшедпук, штат Джаркханд, Індія

Анотація. Механічна обробка скляного матеріалу є надзвичайно важкою через його фізичні та хімічні властивості. Оброблення електрохімічним розрядом є інтегрованим гібридним процесом оброблення провідних матеріалів, високоміцних непровідних матеріалів з високою твердістю і крихкістю. У цьому дослідженні спроектована і виготовлена експериментальна установка для механічного оброблення непровідних матеріалів електрохімічним розрядом. Електрохімічний процес застосовується для свердління отворів у силікатному матеріалі. Експерименти були проведені із застосуванням ортогонального масиву L_{27} методу Тагучі та релізовано у комп'ютерній програмі MINITAB 17. Результати оброблених електрохімічним способом глибини і діаметра отворів у силікатному склі перевірялись з урахуванням таких умов оброблення як напруга, концентрація електроліту і частота обертання. Результати досліджень показали, що основним параметром отримання необхідної глибини і діаметра оброблюваного отвору є у першу напруга. Концентрація електроліту і частота обертання інструмента є також важливими, але другорядними параметрами.

Ключові слова: електрохімічне оброблення, оброблювана глибина, діаметр отвору, метод Тагучі, силікатне скло.