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Material Removal Analysis of Soda-Lime Glass by Using Electrochemical Discharge Drilling Process

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The electrochemical discharge machining is integrated by electro-discharge and electro-chemical manufacturing technology. The soda-lime glass is widely used in various fields such as biomedical, optical and industrial industries. Hence, in present study the electrochemical discharge drilling process is applied on soda-lime glass material to find out the material removal rate. The Taguchi method L_{27} orthogonal array is used for present investigation. The input process parameters are taken as voltage, rotation and electrolyte concentration whereas output response is considered as material removal rate. From this analysis, it is found that voltage is the most dominant parameter for material removal rate followed by electrolyte concentration and rotation for soda-lime glass.

Keywords: Electrochemical discharge machining, Taguchi, Soda-lime glass, Material removal rate, S/N ratio.

INTRODUCTION

In manufacturing industries the high-quality products are obtained by using conventional and non-conventional manufacturing processes, which make changes in size, shape, dimensions and surface quality of the product. Various non-conventional manufacturing methods are applied to machine the brittle and hard materials like glass, ceramics and composites materials [1]. The glass is one of the highest brittle and hard materials, hence it is a challenging task to machine it with conventional and non-conventional manufacturing processes. There are main three categories of glass material *i.e.* soda-lime glass, phosphate glass and borosilicate glass. It is widely used in different fields due to its wide range of excellent properties such as corrosion resistance, high chemical resistance, optical transparency, biocompatibility, attractive appearance, superior optical, high specific strength, heat-resisting capacity, excellent mechanical hardness, excellent anodic bonding, high electrical resistivity, temperature stability, non-porosity, various reflective indices, homogeneity, durability, hydrophilicity and good surface quality. The applications of glass material is production of mirrors, photo-masks, data storage disks, microscopic slides, miniaturization of microfluidic devices for chemical and biological micro total analysis systems, touch screens, mechanical inertial sensors, oxide fuel cells and micro-pumps filters, printed circuit substrates, photographic plates, wafers, chemical apparatus, micro gas turbines, micro-electromechanical systems, mass spectrometry, microcapillary, electrophoresis and opto-mechatronic systems, optical telecommunication, optical industries for spectacle lenses, optical instruments, optical windows and camera lens [2-4]. The glass material can be efficiently machined by using electrochemical discharge machining process (ECDM), which is a combination of electro-discharge and electro-chemical manufacturing process [5]. Hence, from this view the present investigation is undertaken to evaluate material removal rate of soda-lime glass material by applying electrochemical discharge drilling process. The electrochemical discharge machining process is firstly discovered by Kurafuji and Suda [6]. The rate of material removal rises with raising process parameters of voltage and electrolyte concentration [7]. The abrasive cutting tools remarkably improves the material removal rate and machining depth during the electrochemical discharge machining process on borosilicate glass and alumina [8]. The electrochemical discharge machining phenomena ensued only when the supply voltage is beyond the critical voltage *i.e.* the arc region. The different machining mechanism is produced during this process such as melting and vaporization, which is an effect of electrochemical discharges, random thermal stresses, micro-cracking, spalling, high-temperature dissolution, mechanical shock because of expanding gases and electrolyte movement [9]. Sarkar *et al.* developed electrochemical discharge machining setup for micro-drilling experimental work on silicon nitride material. They observed that the applied voltage has a major factor for material removal rate, radial overcut and heat affected zone [10].

Basic mechanism and machining setup of electrochemical discharge machining: Fig. 1 presents basic working mechanism of electrochemical discharge machining process. The

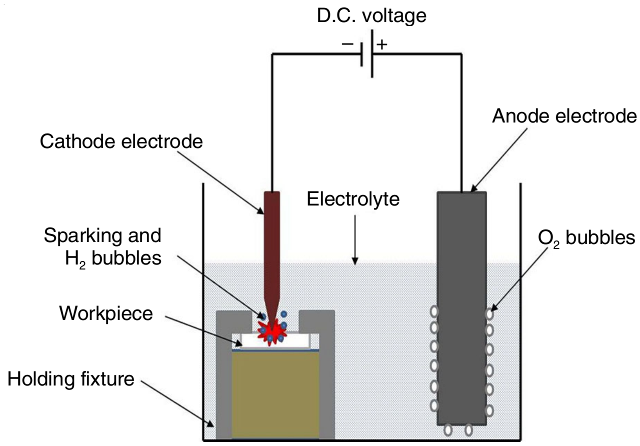

Fig. 1. Basic mechanism of electrochemical discharge machining

cathode and anode tool electrodes are immersed into the electrolyte solution. The size of anode tool electrode is greater than cathode tool electrode. The DC voltage is provided between cathode and anode tool electrodes. When applied voltage is nearly 25 V, then electrolysis takes place thus the formation of oxygen bubbles at the anode electrode is observed. Whereas the hydrogen bubbles get produced at the cathode tool electrode. After increasing more voltage the density of the bubbles increased rapidly. When the applied voltage goes beyond critical voltage it resulted into starting of hydrogen bubbles coalescence at the cathode electrode, which produces a gas film around the tool-electrode. The chemical composition of soda-lime glass material shown in Table-1. The electrochemical reactions during the electrochemical discharge machining process are shown in eqns. 1 and 2 [11].

$$2H_2O + 2e^- \longrightarrow 2(OH)^- + H_2\uparrow \text{ (at cathode)} \quad (1)$$

$$4(OH)^- \longrightarrow 2H_2O + O_2\uparrow + 4e^- \text{ (at anode)} \quad (2)$$

TABLE-1
CHEMICAL COMPOSITION OF SODA-LIME GLASS

Element	SiO_2	Al_2O_3	Na_2O	CaO	MgO	SO_3
Weight (%)	68-75	0-3	11-15	6-11	2-6	0.1-0.4

In this machining process, NaOH is taken as electrolyte, the eqn. 3 shows a chemical reaction in the electrochemical discharge machining process in which glass workpiece dissolves and formation of loose precipitation is observed [12].

$$2NaOH + SiO_2 \longrightarrow Na_2SiO_3\downarrow + H_2O \quad (3)$$

In developed electrochemical discharge machining setup, the movements of X, Y and Z axis are controlled by the compound sliding mechanism. The workpiece is fixed on holding fixture, which is provided with gravity feeding mechanism. The DC voltage supply applied between cathode and anode tool electrode. The cathode tool is attached to the spindle of the stepper motor and this motor is located at the horizontal beam, which is fixed to Z-axis compound slide. The anode tool material is immersed into electrolyte container, which is fixed on a base of X-Y compound slide attached to the table. The cathode tool material is brass of 3 mm diameter having a conical shape. While, the stainless steel 416 of 15 mm diameter and 100 mm length is used as an anode electrode. The working electrolyte solution is taken as NaOH. The machining time is set at 25 min for each experiment.

EXPERIMENTAL

The electrochemical discharge machining micro hole drilled was done on 150 mm × 125 mm × 2 mm soda-lime glass material. On the basis of total degree of freedom needed for an experiment Taguchi L_{27} orthogonal array is designated. The three factors with three levels and their two-way interactions were carried out and then total degree of freedom is obtained *i.e.* 18. As a result, Taguchi L_{27} orthogonal array was preferred, which provides 26 degree of freedom for process parameter combinations. The voltage, rotation and electrolyte concentration are taken as input machining conditions from, which the material removal rate is examined [13]. The material removal rate is defined as the rate of surface material eradicated from the base material, which shows the machining efficiency. In this investigation, material removal was measured by the workpiece weight before and after machining [14]. Table-2 indicates input process parameters and their levels.

TABLE-2
EXPERIMENTAL INPUT PROCESS
PARAMETERS AND THEIR LEVELS

Factor	Parameters	Levels		
		1	2	3
A	Voltage (V)	70	80	90
B	Rotation (rpm)	10	25	40
C	Electrolyte concentration (%)	5	10	15

The experimental outcomes are shown in Table-3 in, which the input process parameter, output responses and the S/N ratios are given. The S/N ratios are evaluated from experimental data through Minitab 17 software. The higher values of S/N ratios indicate better machining performance therefore for material removal rate at higher the better. The material removal rate intended to maximum optimal condition thus larger the better is considered. The S/N ratios are assessed by formula shown in eqn. 4 [15].

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (4)$$

where n represents the number of measurements and y_i is the measured values.

RESULTS AND DISCUSSION

In this experimental work the Taguchi L_{27} orthogonal array is used, which considerably enhances the engineering processes as it reduces the essential time and cost consists of trials. The experimental results data were evaluated by using MINITAB 17 software. The input process parameters of Taguchi method is confirmed by using signal to noise ratio (S/N). From the experimental results it is noticed that the material removal rate rises with the increase in voltage from 70 to 90 V. Thus, due to the increase in voltage, the rate of gas bubbles formation get increases, which follows on a large quantity of discharge energy in the sparking zone. Likewise, the improved material removal is seen, which is an effect of the electrolyte concentration percen-

TABLE-3
TAGUCHI L_{27} ORTHOGONAL ARRAY, EXPERIMENTAL RESULTS AND S/N RATIOS OF RESULTS

Run	Voltage (V)	Rotation (rpm)	Electrolyte conc. (%)	Material removal rate (mg/min)	Signal to noise ratios
1	70	10	5	0.047	-26.5580
2	70	10	10	0.064	-23.8764
3	70	10	15	0.083	-21.6184
4	70	25	5	0.045	-26.9357
5	70	25	10	0.070	-23.0980
6	70	25	15	0.065	-23.7417
7	70	40	5	0.052	-25.6799
8	70	40	10	0.075	-22.4988
9	70	40	15	0.088	-21.1103
10	80	10	5	0.140	-17.0774
11	80	10	10	0.220	-13.1515
12	80	10	15	0.280	-11.0568
13	80	25	5	0.170	-15.3910
14	80	25	10	0.280	-11.0568
15	80	25	15	0.330	-9.6297
16	80	40	5	0.180	-14.8945
17	80	40	10	0.260	-11.7005
18	80	40	15	0.310	-10.1728
19	90	10	5	0.240	-12.3958
20	90	10	10	0.380	-8.4043
21	90	10	15	0.470	-6.5580
22	90	25	5	0.270	-11.3727
23	90	25	10	0.440	-7.1309
24	90	25	15	0.500	-6.0206
25	90	40	5	0.260	-11.7005
26	90	40	10	0.410	-7.7443
27	90	40	15	0.520	-5.6799

tage caused due to the increased amount of current, which helps to accelerate the electrolysis process subsequent into high-intensity hydrogen gas bubbles arises at the cathode electrode [16,17].

Fig. 2 presents mean S/N ratios plot of material removal rate. It indicates influence of voltage, rotation and electrolyte concentration input process parameters on material removal rate. Hence, according to this figure voltage is the key parameter for material removal followed by electrolyte concentration and rotation. Figs. 3-5 shows the 3D surface plot for material removal rate *vs.* voltage, electrolyte concentration and rotation.

The ANOVA is used to examine the influence of individual process parameters on output response, which is shown in Table-4. In this table, the delta value indicates the difference

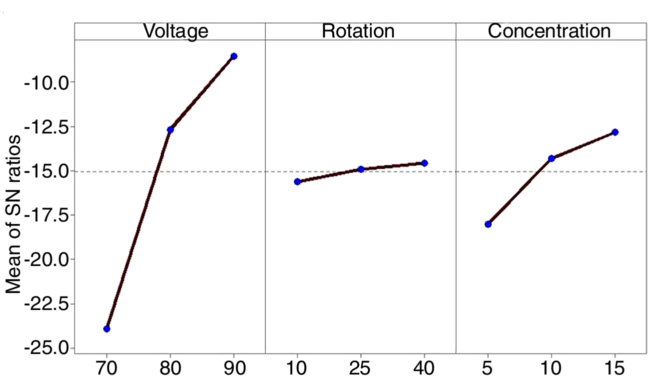

Fig. 2. Mean S/N ratios plot for material removal rate

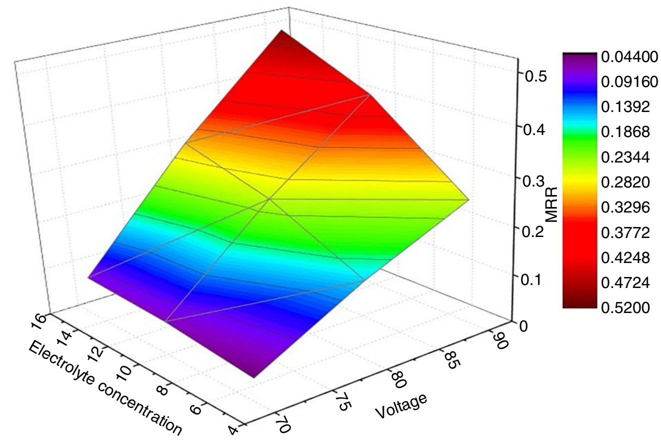

Fig. 3. 3D surface plot for material removal rate *vs.* voltage and electrolyte concentration

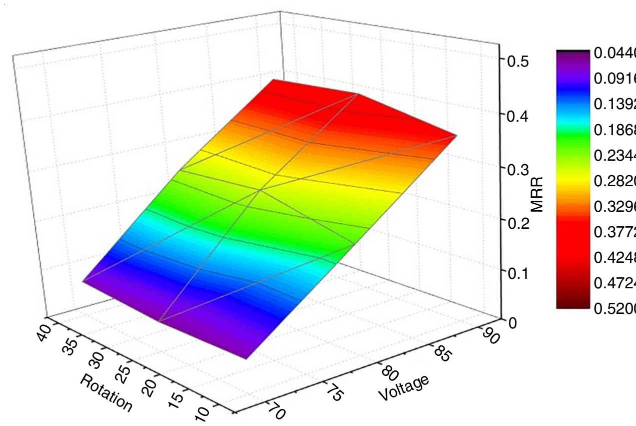

Fig. 4. 3D surface plot for material removal rate *vs.* voltage and rotation

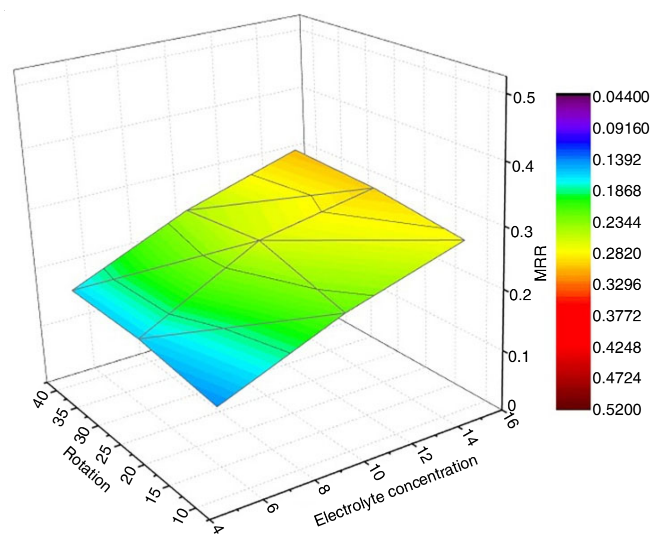

Fig. 5. 3D surface plot for material removal rate *vs.* electrolyte concentration and rotation

between maximum and minimum average value of S/N ratios of each process parameters. It also specifies the optimal level of parameters, which are selected on bases of higher values in S/N ratios table. In ANOVA table the P-value illustrates significance process parameters. If the P-value is smaller than 0.05 then the parameter is significant, therefore the voltage and electrolyte concentration are the most significant parameters. Table-5 shows response characteristic of S/N ratios for material

TABLE-4
ANOVA TABLE FOR MATERIAL REMOVAL RATE

Source	DF	Adj SS	Adj MS	F value	P value
Voltage	2	0.468806	0.234403	125.52	0.000
Rotation	2	0.004226	0.002113	1.13	0.342
Electrolyte concentration	2	0.087941	0.043970	23.55	0.000
Error	20	0.037348	0.001867		
Total	26	0.598321			

S	R^2	R^2 (adj.)	R^2 (pred.)
0.0432134	93.76 %	91.89 %	88.62 %

TABLE-5
RESPONSE TABLE FOR S/N RATIOS OF MATERIAL REMOVAL RATE

Level	Voltage (V)	Rotation (rpm)	Electrolyte concentration (%)
1	-23.902	-15.633	-18.001
2	-12.681	-14.931	-14.296
3	-8.556	-14.576	-12.843
Delta	15.346	1.057	5.157
Rank	1	3	2

removal rate, which is average for each level of per factor. The table identifies the ranks based on delta measurements. The ranks based on delta values *i.e.* rank 1 for utmost delta value then rank 2 for next greatest delta value, *etc.* The rank indicates the consequence of each factor in the response. The delta and ranks values approved that the voltage has highest effect on material removal rate, which is followed by electrolyte concentration and rotation. A mathematical model for material removal rate is developed by using MINITAB 17 software, which is shown in eqn. 5.

$$\text{Material removal rate} = -1.2173 + 0.01612\ \text{Voltage} + 0.000856\ \text{Rotation} + 0.0138\ \text{Electrolyte conc.} \quad (5)$$

Conclusion

The soda-lime glass material is widely used in biomedical and optical industries but it has high hardness and high brittleness, which make it very difficult to machine. The electrochemical discharge machining is one of the integrated manufacturing process, which can machine soda-lime glass material easily and economical perspective. In this investigation, the electrochemical discharge machining setup is fabricated and applied for the micro-drilling of soda-lime glass material. From the experimental analysis, it can be concluded that the voltage is a most dominant factor during electrochemical discharge machining micro-drilling process. The second most dominant factor is electrolyte concentration, which also significantly contributes during this process. The low rotation speed of cathode is a least significant parameter. The maximum material removal is achieved at 90 V, 15 % electrolyte concentration and 40 rpm speed of the rotation for soda-lime glass material.

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