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FABRICATION OF MICRO FEATURES ON QUARTZ GLASS USING DEVELOPED WECDM SETUP

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ABSTRACT

In today's high-tech demand-oriented society everything is getting faster and smaller. Proper selection of materials and their miniaturization has become very challenging. Composites, ceramics, glass and smart materials are becoming more and more popular because of their superiority over conventional materials but their miniaturization for particular applications is difficult. In this experimental study, Wire electro chemical discharge machining (WECDM) setup was developed to machine Quartz glass material. The experiments were performed for Material removal rate (MRR) and Width of cut (WOC) for different governing input parameters using Taguchi design of experimentations. Optical microscope (OM) shows the fine cut of 0.120mm width. The results show the need for the secondary process to improve topography of machined surface. The toxic fumes generated across electrode is a challenge for the effectiveness of the process.

Keywords: OM, aspect ratio, MRR, WOC, miniaturization, quartz glass, WECDM.

INTRODUCTION

Quartz glass material is used in accelerometer sensor, lenses, fixtures, micro-patch antenna, MEMS etc. The machine-ability is the challenge because of its brittleness and non-conducting nature. Conventional machining is not possible because of its hardness and brittleness; further miniaturization creates more trouble for researchers. Diamond cutting creates cracks in the glass. Moving towards advanced machining processes such as water jet machining, abrasive waterjet machining, they are not controllable and can't generate full microfeatures. Laser beam machining, ion beam machining creates the problem of taper cut and consumes very high power. Electric discharge machining(EDM) and electric chemical machining (ECM) is not possible due to non-conducting nature of the material. WECDM is one possible solution to machine the glass in a controlled manner, this is a hybrid process that uses advantages of both processes (EDM & ECM) and overcomes the shortcoming of the same process. Since the process is not commercially available, so the authors have developed the setup as shown in Figure-1. The material is removed by both chemical and discharge phenomena. The non-conductive material taken as a workpiece is machined through melting and vaporizing process. Due to the electrochemical reactions, hydrogen bubbles generated at cathode (wire) and electrolyte interface and oxygen is liberated at the anode. As the voltage is gradually increased, the bubbles begin to form rapidly due to a simultaneous increase in current density. The heat generated due to the flow of current evaporates the electrolyte too and the cathode is shielded by an electrically non-conductive gaseous layer of hydrogen and vapor mix. When the applied voltage exceeds the potential gradient across the insulated gaseous layer, its breakdown occurs in form of discharge (spark) along with heat. This heat is enough to melt and evaporate the hard and brittle workpiece such as quartz glass.The fumes(gas) generated at electrode are partially toxic in nature.

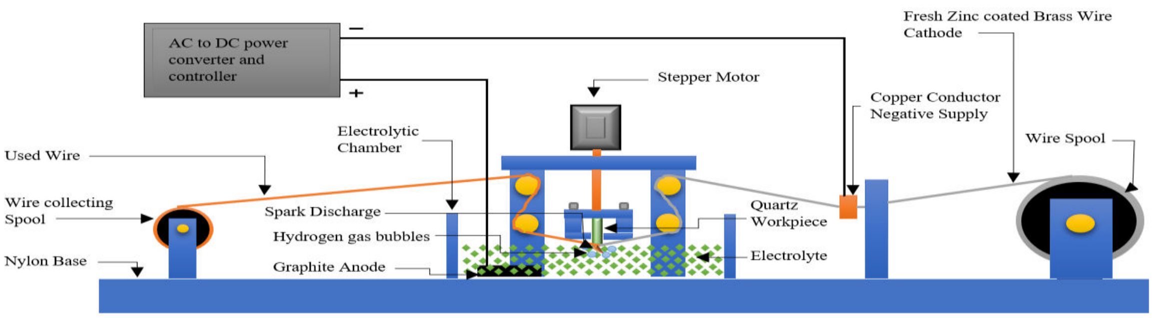

Figure-1. WECDM set-up

The intensity of spark varies with the voltage across electrodes, electrolyte conductivity, and bubble size. The theory of spark generation can be attributed to interrupter switches analogy of electrical circuit. If the inductance of the circuit is L, then at the instant of opening the circuit the induced electromotive force (emf) $V = -L(dI/dt)$, where 'I' is the current at any instant of circuit opening and 't' is the time to break the circuit. This induced emf is termed as switching emf and the energy stored in the inductance is released through spark. The intensity of the spark is utilized to remove the material from the surface.

LITERATURE SURVEY

Bhuyan *et al* [1] conducted experiments to analyze the effects of the supply voltage, pulse on-time and electrolyte concentration on the material removal rate(MRR) and surface roughness (R_a) of borosilicate glass, they found MRR and R_a increase with an increase up to 20% concentration and after that it starts to decrease. The surface finish is more prominent if KOH is used as it forms small molten area. Increase in wire feed rate prevents the secondary discharge and improves the expansion reduction as suggested by Yang *et al* [2]. They conducted experiments on pyrex glass using 0.25mm brass wire as the cathode to study the effect of adding SiC abrasive with different concentration and grit size to electrolyte on the slit expansion MRR and cut surface roughness. Also, the other various parameters that were varied to test results on slit expansion MRR and cut surface roughness were power frequency, duty factor, electrolyte, wire tension, and wire feed rate. Kuan Yuan Kuo et *al* [3] performed WECDM under titrated electrolyte flow with the addition of SiC powder and found that if the feed rate of the workpiece equals the etching rate by the electrolyte, minimum surface roughness can be obtained. Nav Rattan *et al* [4] used a magneto-hydrodynamic (MHD) convection process to increase the electrolyte flow in traveling wire electrochemical spark machining process and observed an improvement in MRR varying from 9.09% to 200% for various processing conditions. YP Singh *et al* [5] developed a TW-ECSM set up to machine electrically partially conductive materials like piezoelectric ceramic - lead zirconate titanate (PZT) and fiber epoxy composites and concluded that this process can be used to machine these materials provided proper feed rate is given. N.S. Mitra *et al* [6] done an analysis of traveling wire electrochemical discharge machining of hylam based composites using Taguchi method. He observed that pulse on time and concentrations of electrolyte are significant factors for material removal rate whereas applied voltage, the concentration of electrolyte and wire feed rate are significant factors for radial overcut. Amrinder Singh *et al* [7] conducted experiments to reduce wire breakage problem while machining fine slots through an optimum parametric setting of voltage, electrolytic concentration. They also studied the effects on MRR, length of cut and width of cut. The wire used was of 0.20mm of zinc diffused brass material and KOH electrolyte was used. Manna *et al* [8] developed a TWECSM setup to machine Al_2O_3 ceramics and performed a specific number of experiments based on Taguchi design to find the most significant parameter affecting the material removal and spark width gap. Tandon *et al* [9] performed ECSM for cutting and drilling holes in Kevlar fibre epoxy and glass fibre epoxy materials and observed MRR (Material Removal Rate), TWR (Tool Wear Rate), and OC (Over Cut) to increase in proportion with voltage. Han *et al* [10] proposed roughening of the wire used in WECDM to improve surface integrity and spark discharge distribution. Cao *et al* [11] used a mechanical contact detector to reduce the immersion of the tool electrode in the electrolyte to minimum possible depth. By doing that they observed a stable gas film at low voltage which improved the machining of 3D micro-structure of glass. Adhikary *et al* [12] used cathode and anode as a tool using reverse and direct polarity in ECSM of quartz glass and compared various results. They observed deep craters and higher cutting rate at reverse polarity but tool wear, surface roughness and overcut were also higher as compared to direct polarity. Bhattacharyya *et al* [13] used modular mechatronic features to develop ECDM setup to perform experiments on aluminium oxide ceramic workpiece. Through experiments, they proposed an optimized value of voltage and NaOH electrolyte concentration to 80V and 25% respectively. Also taper tool with flat front tip were best for controlled machining. Peng *et al* [14] observed pulsed DC power to give better spark stability and more spark energy release as compared to constant DC power. Also, frequency, duty factor, ion translation rate, electrolyte immersing depth and the concentration of electrolyte were found dominant factors in ECDM. Balwinder Singh *et al* [15] studied various factors of ECDM and their affects on Material removal, surface finish and tool wear rate. Also, optimized range of parameters by different optimizing techniques were suggested. Mediliyegedara *et al* [16] developed a new control process for ECDM process using real time controller. V.K. Jain *et al* [17] studied effects of voltage and electrolyte concentration on MRR, diametral overcut, tool wear rate on glass-epoxy and Kevlar-epoxy composites using NaOH as electrolyte on a TW-ECSM process. They found the increase in voltage makes MRR higher because discharge energy per spark increase with higher voltage making effectively higher MRR. Sarkar *et al* [18] developed a mathematical model using voltage, electrolyte concentration, working gap for MRR and radial overcut. Later, Sarkar *et al* [19] investigated effect of various parameters on tool wear rate using NaOH solution. Fascio *et al* [20] stated WECDM is an effective technique to machine hard to machine nonconductive material, but this process has certain limitations and challenges like wire breakage, optimum MRR, surface roughness, overcut etc. This experimental study is an attempt to improve the process.

Figure-2. Actual WECDM setup.

The nylon sheet of thickness 20mm is used to make the body, including the small pulleys to guide the wire to maintain the tension. The non-reusable zinc coated brass wire is mounted to right side of the roller, guiding through the point (cathode) to another roller on the other side governed by the stepper motor operating at the voltage 3.3V having step angle 1.8 degrees. The workpiece quartz glass is kept at a fixture; the motion of feed is further controlled by another stepper motor. The motion of both motors is controlled by the CNC Mach3 software operated on the laptop as shown in the Figure-2. The constant DC power supply is used to control the voltage for the process. A small 30 minutes' power back up is given as by UPS to ensure the uninterrupted power supply. Machining was performed on 25 × 75 × 1 mm quartz glass using zinc coated brass wire with NaOH as the electrolyte at various concentrations.

In the beginning, a number of trial experiments were conducted in order to check the range of input parameters. Abrupt breakage of wire was observed when the voltage was increased beyond a certain value. If the electrolyte-wire contact is not adequately in synchronization with machining rate, then either the spark doesn't occur or becomes too wide which in some cases leads to wire breakage. Keeping the trail runs, literature survey and expert suggestion a suitable design of experimentation (DOE) was prepared as shown in Table-1.

Table-1. Machining parameters.

Input parameters			
Factors	**Low (1)**	**Medium (2)**	**High (3)**
A - Voltage (V)	25	35	45
B - Electrolyte Concentration (w/v %)	10	20	30
C - Wire speed (mm/s)	8.6127	9.8864	11.7470
Fixed parameters			
Workpiece - Quartz glass		Wire tension - 70%	
Tool - Zn coated brass wire		Polarity - Tool cathode negative polarity	
Electrolyte - NaOH		Current - 0.8Amp	
Output parameters			
Material Removal Rate (MRR)		The width of Cut (WOC)	

For experimental analysis using Taguchi method, the L_9 orthogonal array was considered. The degree of freedom for chosen three input parameters or factors having three variables or levels each comes out to be six and two degrees of freedom is considered for error. This exercise makes a total degree of freedom to 8. The degree of freedom (dof) for the orthogonal array should be greater than or equal to that of the input parameters.

Table-2. Orthogonal array for L_9.

Exp. No.	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

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EXPERIMENTAL RESULTS

As per the L_9 orthogonal array, the experiments were performed and each experiment was tried for three times. MRR and WOC as output parameters were considered for observation. WOC was measured on Zeiss optical microscope. The observed values are depicted in Table-3. Figure-3,4 shown below are some of the images showing the micro groove at various different conditions.

Table-3. Experimental values.

Experiment number	Voltage (V)	Electrolyte concentration (w/v %)	Wire speed (mm/s)	MRR (mg/min)	WOC (mm)
1	25	10	8.6127	0.008672	0.108
2	25	20	9.8864	0.008902	0.112
3	25	30	11.7470	0.008844	0.111
4	35	10	9.8864	0.019320	0.139
5	35	20	11.7470	0.023940	0.143
6	35	30	8.6127	0.022440	0.141
7	45	10	11.7470	0.181005	0.171
8	45	20	8.6127	0.182896	0.178
9	45	30	9.8864	0.182160	0.175
Mean				0.070908	0.142

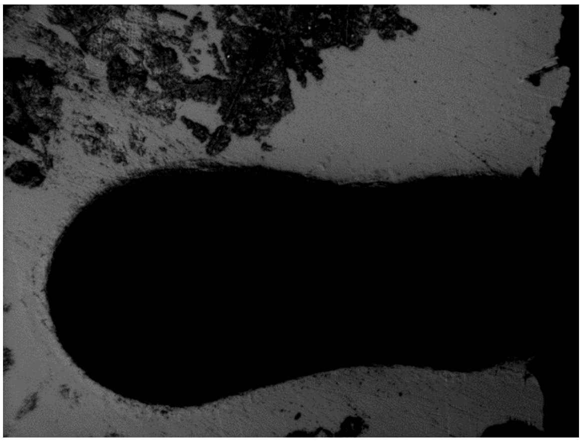

Figure-3. A groove machined at 25 voltswith 30% w/v conc. of electrolyte andat 11.7470 mm/s wire speed.

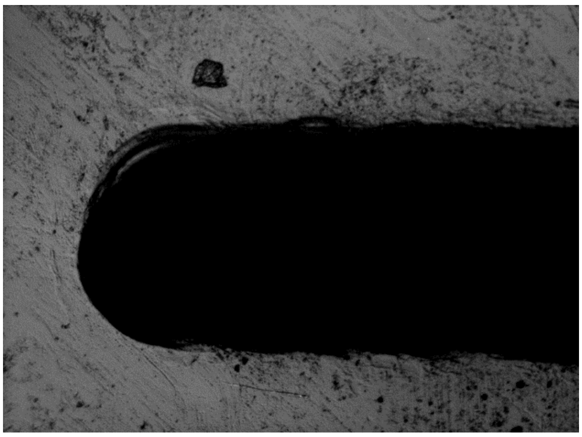

Figure-4. A groove machined at 35 voltswith30% w/v conc. of electrolyte and at 8.6127 mm/s wire speed.

OPTIMIZATION

In this experimental design, two types of S/N ratio have been used higher-the-better for MRR and lower-the-better for WOC. The response table no.5 for output parameters is generated by taking the values from the considered characteristic parameter for a particular level of the orthogonal array table no.3 and then taking it mean within the same level. For example, the effect on WOC for input parameters A - voltage at level 1 can be calculated as:

$A_1 = (0.108 + 0.112 + 0.111)/3 = 0.11033$

Using the same approach response tables were produced for MRR and WOC as shown in the table no. 4 and 5. Graph 1 and 2 shows the S/N ratio plots for MRR and WOC. The input parameter combination for optimum results for MRR and WOC are $A_3B_2C_3$ and $A_1B_1C_1$ respectively.

Table-4. Response table for MRR (mg/min).

Level	Voltage (V)	Electrolyte conc (w/v %)	Wire speed (mm/s)
1	0.008806	0.069665	0.071336
2	0.021900	0.071912	0.070127
3	0.182020	0.071148	0.071263

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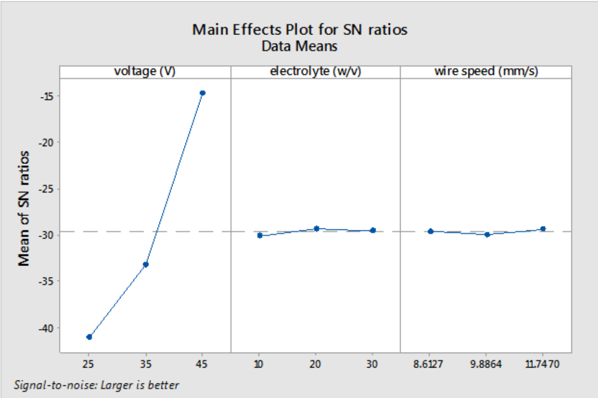
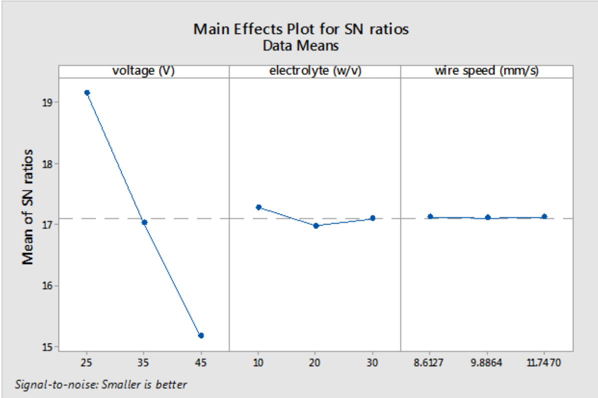
Table-5. Response table for WOC (mm).

Level	Voltage (V)	Electrolyte conc (w/v %)	Wire speed (mm/s)
1	0.11033	0.13933	0.14233
2	0.14100	0.14433	0.14200
3	0.17466	0.14233	0.14166



Graph-1. S/N ratio for MRR.



Graph-2. S/N ratio for WOC.

PREDICTIONS OF OPTIMAL RESULTS

For the prediction of optimized results of machining parameters, only significant input parameter values are considered which are found from analysis of variance (ANOVA) table and the value in itself is obtained from the relation below:

$$V_{opt} = V_m + \sum_{i=0}^{n} (V_i - V_m)$$

where V_{opt} is the optimized result, V_m is the mean of all the values of the output parameter under consideration, V_i is the value at the optimum level obtained from response table and n is the number of significant input parameters obtained from ANOVA table.

Table-6. ANOVA table for MRR.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
voltage (V)	2	0.055813	0.027907	23565.40	0.000
electrolyte (w/v)	2	0.000008	0.000004	3.31	0.232
wire speed (mm/s)	2	0.000003	0.000001	1.16	0.462
Error	2	0.000002	0.000001		
Total	8	0.055826			

Table-7. ANOVA table for WOC.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
voltage (V)	2	0.006213	0.003106	2329.75	0.000
electrolyte (w/v)	2	0.000038	0.000019	14.25	0.066
wire speed (mm/s)	2	0.000001	0.000000	0.25	0.800
Error	2	0.000003	0.000001		
Total	8	0.006254			

ANALYSIS OF RESULTS

Tables 6 and 7 suggest that only one input parameter namely Voltage is the most significant factor under 95% confidence level which affects MRR and WOC as the p-value ≤ 0.05 in each case at 95% confidence interval. Wire speed has the least significant effect on both

MRR and WOC. Since voltage is the only one significant factor affecting the results, therefore, only this parameter will be taken into consideration for predicting optimal MRR and WOC values. Using equation (1) the predicted optimum value for MRR and WOC is calculated as follows:

V_{opt} (MRR) = 0.070908 + (0.182020 – 0.070908)
= 0.182020
V_{opt} (WOC) = 0.142 + (0.11033 – 0.142)
= 0.11033

Table-8. Optimal values.

Output Parameter	Optimal parameter combination	Significant parameters (at 95% confidence level)	Predicted optimal value	Experimental value
MRR	$A_3B_2C_3$	A	0.182020 (mg/min)	0.17739 (mg/min)
WOC	$A_1B_1C_1$	A	0.11033 (mm)	0.14102 (mm)

CONCLUSION AND FUTURE CHALLENGE

In this study, the objective was to cut precise microgrooves on quartz glass and govern the accuracy of the process. The microgrooves are possible on quartz glass but the surface finish will get compromised against MRR. Experimental and predicted resulted are nearly equal. Microscopic images show slight chips and burrs across the edges which require secondary processes for finishing. Frequent wire breakage, the setting of wire tension, preciseness and surface finish are challenges. Further, the process can be improved by using a pulsed power source, magnets, use of micro-level abrasives along with CNC control of the machine.

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