Analysis on electrochemical discharge machining during micro-channel cutting on glass

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Abstract: Modern industrial field of micro-machining has an attractive attention to increase the machinability of electrically non-conducting materials. Electrochemical discharge micro-machining process has the ability to machine high strength non-conducting brittle materials like glass. This paper shows a development of second-order correlation between the various machining criteria and different process parameters such as applied voltage, electrolyte concentration and inter-electrode gap (IEG). The analysis of variance (ANOVA) has been performed to find out the adequacy of the developed models. The research paper includes the effects of various process parameters on material removal rate (MRR), overcut (OC), heat affected zone (HAZ) and machining depth (MD) during micro-channel generation on glass. This paper also represents the single as well as multi-objective optimised results to determine the suitable parametric combination for maximum MRR and machining depth and minimum overcut and HAZ area using response surface methodology (RSM) and genetic algorithm (GA).

Keywords: ECDM; electrochemical discharge machining; micro-channel; RSM; response surface methodology; GA; genetic algorithm; glass.


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non-conventional machining processes such as electrical discharge machining (EDM), electrochemical discharge machining (ECDM) and micro-machining of advanced materials etc.

B. Doloi is a Professor and former Head of Production Engineering department of Jadavpur University. He completed PhD Research work and received PhD (Engineering) in 2001 in the area of Electrochemical Discharge Machining. He also received Young Scientist Award from DST, New Delhi in 2002. He was the Principal Investigator of DST sponsored research project and CSIR sponsored research Project on the area “Laser beam machining of Engineering Ceramics” and also DST PURSE project of JU. He is also a co-Principal investigator of BARC sponsored Research Project on Electrochemical Micro-machining. He has published about 56 journal papers in international and national levels in the area of advanced manufacturing technology and about 116 research papers in reputed national and international seminars and conferences. Under his supervision, 10 PhD theses have been awarded and eight PhD theses are in progress.

B. Bhattacharyya is a Professor and former Head of the Production Engineering Department and Coordinator of Centre of Advanced Study (CAS) Programme under University Grants Commission (UGC) and Quality Improvement Programme (QIP) under AICTE of Jadavpur University. His research areas include non-traditional machining, micromachining and advanced manufacturing systems. He has published 108 research papers in national and international journals and 271 research papers in national and international conferences. He has completed several research projects. He is recipient of various awards, e.g., Gold Medal and Certificate of Achievements for research papers and theses as well as the Career Award of the UGC, New Delhi, India.

1 Introduction

Micro-machining is the basic technology used for the production of miniature parts and components. Again electrically non-conducting materials like glass is gaining the popularity in micro-fluidic devices because of its corrosion resistance, high hardness, inert in nature, high strength and refractoriness properties. Electrochemical discharge machining process has the potential for generating micro-channel on glass for the utilisation in micro-fluidic devices. In electrochemical discharge machining (ECDM) process, the material is removed due to combined effects of electrochemical (EC) reactions and electrical spark discharge (ESD) action as illustrated by Basak et al. (1996), Bhattacharyya et al. (1999) and Jain et al. (1999). Many researchers have carried out research in order to trounce over the various drawbacks associated with the ECDM process. Peng et al. (2004) documented that the travelling wire electrochemical discharge machining (TW-ECDM) could be applied for slicing meso-size non-conducting brittle materials like optical glass and quartz bars of several millimetres thick. Sarkar et al. (2006) showed the effects of various process parameters during micro-drilling on silicon nitride ceramic by ECDM. Han et al. (2007) reported a new method for improvement of the surface integrity of ECDM process by mixing fine graphite powder with electrolyte. West and Jadhav (2007) described ECDM method for fluidic interfacing through thin glass substrates and formation of spherical micro cavities and presented the optimum conditions for rapid and reproducible through-hole machining on both 500 µm thick and
fragile of 180 µm thin borosilicate glass substrates. Sarkar et al. (2008) analysed that the quality of the holes on Al₂O₃ and ZrO₂ during micro-drilling greatly depended on the applied voltage and electrolyte concentration. Sarkar et al. (2009) designed and searched out the suitable power circuit configuration for micro-machining operation on glass by ECDM. Cao et al. (2009) experimentally showed that the micro-electrochemical discharge machining (micro-ECDM) process improved the machining of 3D micro-structures on the glass and obtained a good surface with minimised structures during drilling and milling operations. Kulkarni (2009) experimentally represented the qualitative formulation of the discharge formation and material removal mechanism of ECDM process and also the energy density associated with single discharge during micro-machining. Wüthrich and Allagui (2010) discussed the fabrication of nanoparticles and several applications of interest in catalysis and biomedical domain. Ranganayakulu et al. (2011) analysed that the volume of material removed decreased with increasing machining depth. Ziki et al. (2012) demonstrated that electrolyte viscosity was the most significant factor influencing the channel texture. Jui et al. (2013) fabricated micro-tools with high aspect ratio of 11 which had been used for deep micro-hole drilling on glass using low electrolyte concentration. Jain and Priyadarshini (2014) fabricated microchannels of different shapes in ceramics (quartz) using electrochemical spark micromachining (ECSMM) and were able to obtain the microchannels of the minimum width of 144 µm. Gupta et al. (2016) found that the pulse duration has a great effect to achieve better control on quality characteristics and aspect ratio of glass material machined by the ECDM process. Jiang et al. (2014) and Baoyang et al. (2015) used tapered tool electrodes to improve the consistency of spark generation to suppress the generation of minor discharges and also presented an analytical model of the gas film which was involved in bubble growth and departure on electrode, gas film evolution, electrolysis characteristics and the range of thickness of gas film. Hajian et al. (2016) demonstrated that when the magnetic field was applied, the machined surface would be smoother for the lower values of electrolyte concentration and higher machining voltages, so the machining depth will increase. Goud et al. (2016) reported the concepts of material removal mechanism in ECDM as review and the possibility of future efforts to enhance the material removal rate (MRR) of the ECDM.

From the past literature survey, it is cleared that no work has been carried for studying the effects of process variants and searching out the optimal machining condition for better performance during micro-channel cutting on glass. Therefore, the objectives of the paper are to develop a second order correlation between the different machining criteria e.g., MRR, Overcut (OC), HAZ and machining depth (MD) and various process parameters such as applied voltage (V), electrolyte concentration (wt %) and inter-electrode gap (IEG) (mm) and to study the effects of these process parameters on above machining criteria during micro-channel generation on glass by the ECDM process. The analysis of variance (ANOVA) has been performed to justify the adequacy of the developed models. This paper also presents the single as well as multi-objective optimised parametric combination for achieving maximum MRR and machining depth and minimum overcut and HAZ area using the response surface methodology (RSM) and genetic algorithm (GA).
2 Experimentation

ECDM is a hybrid non-conventional machining process consisting of electro-chemical machining (ECM) and electro-discharge machining (EDM). In the ECDM process, the electrolyte cell is similar to that used in ECM. The workpiece is dipped in an appropriate electrolyte solution (typically sodium hydroxide or potassium hydroxide). A constant DC voltage is applied between the machining tool or tool-electrode and the auxiliary electrode with proper polarity, generally positive terminal as an anode (auxiliary electrode) and negative terminal as a cathode (tool-electrode). The tool-electrode surface is always significantly smaller than the auxiliary electrode surface (by a factor of 100). When tool touches the job, there are micro-gaps present both in the surface of tool-electrode and job due to surface irregularity. The electrolyte present in micro-gaps is responsible for the generation of gas and vapour bubbles in the micro-gaps and surroundings of tool surface. The generation of combined gas and vapour bubbles takes place due to electrochemical reactions in ECM and joule heating of electrolyte respectively. The bubbles thus formed ultimately form an insulating gas film layer around the tool-electrode. When the applied voltage gradient is sufficient to breakdown this gas bubbles layer between the tool-electrode and workpiece i.e., beyond a threshold value, a conductive path is developed for the spark discharge owing to the ionisation of the gas bubbles, which thereby causes the flow of a large amount of current. Then electro-discharge action takes place between the tool (cathode) and the electrolyte across the gas bubble layers in the electrolyte. When an electrically non-conducting workpiece is placed in the closed vicinity of the sparking the electrons strike the workpiece material and as a result temperature of the spot hit by the electrons may rise to a very high value. This discharge phenomenon occurs within few micro-seconds. When this temperature is above the melting temperature of the workpiece, the material is melted and vapourised and finally removed. The material of workpiece is removed due to the effect of thermal spalling (Bhattacharyya et al., 1999) also.

2.1 Experimental set up

After proper understanding of the fundamentals of the micro-ECDM process and also in order to meet all the objectives of the present research, a developed ECDM system has been used for micro-machining operation. The schematic diagram of experimental micro-ECDM set-up is shown in Figure 1. The system consists of several subsystems such as

- mechanical unit
- the electric power supply unit
- electrolyte supply unit with a size of machining chamber $100 \times 80 \times 5$ mm.

2.2 Experimental scheme

In the current research work, three process parameters were considered such as voltage, electrolyte concentration and IEG. Unlike ECM or EDM process, the IEG in ECDM process is similar to the machining gap. In ECDM the IEG is referred as the gap between two electrodes i.e., tool-electrode (cathode) and the auxiliary electrode (anode) since here
the workpiece material is an electrically non-conducting whereas machining gap is considered as the gap between tool-electrode and workpiece material. The machining gap is very short in the range of several microns as compared to the IEG, which is several millimetres in this process. The IEG plays vital a role in the ECDM process. The current flow in the IEG changes with the variation of gap resistance, which in turn depends on the length of IEG. So the machining rate in ECDM process varies with the change in IEG. The IEG was set at 30 mm, 35 mm, and 40 mm. The selection of electrolyte is one of the important parameters for this kind of machining process because the concentration of electrolyte influences the chemical reactions. NaOH solution was used as an electrolyte for this experiment. The electrolyte concentrations were varied at 15, 22.5 and 30wt%. The flow of electrolyte was not considered because it removed the gas bubbles generated during the machining operation, resulting in weak sparking and low material removal.

**Figure 1** Schematic diagram of micro-ECDM experimental setup (see online version for colours)

The other important task was to select the nature of power supply and the voltage range. Here, pulsed DC power supply was selected and experiments were carried out at three different voltage levels viz. 50 V, 55 V and 60 V. By applying the pulsed DC voltage instead of continuous DC voltage the changes in the electrolyte composition and the temperature rise and also the change of electrical resistivity can be avoided. Again the current efficiency is much more depended on the current density when a pulsed voltage is used than the use of continuous voltage. With the continuous DC voltage, the efficiency decreases gradually when the current density is reduced whereas with the pulsed voltage the decrease is much more rapid. A steep fall in efficiency with decreasing...
current density depends upon the pulse duration and to somewhat lesser extent on the interval. By using pulsating current extremely high instantaneous current density can be applied in the IEG without the need for an elaborated electrolyte pumping system and rigid machine frame. This is followed by a relaxation time of zero current, which allows for removal of reaction products and heat from the IEG. Pulsed DC power supply consists of constant DC and variable components. By suitable choice of the variable component of pulsating current, the electrolyte conductivity can be changed and the high instantaneous mass transportation can be attained even at low electrolyte flow rate. Also, MRR with low HAZ was found to be greater for pulse setting DC than DC and the tool life also increased in pulse DC (Paul and Korah, 2016). The experiments were conducted by using a pure DC power supply. The ranges of above three process parameters were chosen by the trial and error method.

Rectangular shaped thin sheet with flat face of length 8 mm and thickness 100 µm was used as micro-tool. The length of the µ-channel cut by this tool electrode was almost equal to the length of the tool and the tool length was chosen based on the experimental observations. If the length of the tool is more than the present tool length, the glass workpiece breaks due to high thermal spalling. Stainless steel was the material for the micro-tool electrode because it has high corrosion resistance and high melting point.

Metal removal rate, overcut, HAZ area and machining depth were considered as performance criteria of machined micro-holes where, MRR is calculated by weight difference of workpiece before and after machining per unit machining time and overcut is calculated by subtracting the thickness of tool electrode from the width of the channel. Machining depth has been determined by taking the cross-sectional view of micro-channels with the Leica microscope and HAZ area also was measured with the same instrument. The weight of the job was measured with Mettler Toledo weighing machine (LC of $1 \times 10^{-2}$ mg). The width of cut (WOC), machining depth and HAZ area were measured at the magnifications of 5X, 10X and 20X respectively with Leica microscope. Table 1 shows the properties of Silica glass materials. Also, other experimental conditions and the ranges of parameters are exhibited in Table 2.

Experimentation was conducted based on rotatable face centred design (FCD) of RSM (Montgomery, 1997) using a developed micro-ECDM set-up. In this experimental investigation for micro-machining with ECDM, the upper level of each variable was coded as +1 and the lower level as –1 for every process parameters in order to design the experiments in an optimised way. The general second order polynomial equation based on response surface method, which correlates various process parameters with different machining criteria, is described as follows:

$$Y_i = b_{0} + \sum_{i=1}^{n} b_{i}X_{i} + \sum_{i=1}^{n} b_{i}X_{i}^2 + \sum_{i<j} b_{ij}X_{i}X_{j} + \epsilon,$$  \hspace{1cm} (1)

where

$Y_i$: the corresponding response, e.g., MRR, OC, HAZ and MD

$X_{i}$: the coded values of the $i$th machining parameters for $ith$ experiment

$\epsilon$: the error

$n$: number of machining parameters

$b_{i}$, $b_{ij}$: second order regression coefficients.
Table 1  Properties of silica glass materials

<table>
<thead>
<tr>
<th>Properties</th>
<th>Silica glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (Kg/m³)</td>
<td>$2.52 \times 10^3$</td>
</tr>
<tr>
<td>Thermal conductivity (W/m-k)</td>
<td>1.2</td>
</tr>
<tr>
<td>Thermal expansion (K⁻¹)</td>
<td>$0.54 \times 10^{-6}$</td>
</tr>
<tr>
<td>Young’s modulus (N/m²)</td>
<td>$72 \times 10^9$</td>
</tr>
<tr>
<td>Tensile strength (N/m²)</td>
<td>$50 \times 10^6$</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.518</td>
</tr>
<tr>
<td>Melting temperature (ºC)</td>
<td>1400</td>
</tr>
</tbody>
</table>

Table 2  Ranges and levels of different machining parameters

<table>
<thead>
<tr>
<th>Machining parameters</th>
<th>Ranges/level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable parameters</td>
<td></td>
</tr>
<tr>
<td>Applied voltage</td>
<td>50–60 V/50, 55, 60</td>
</tr>
<tr>
<td>Electrolyte concentration</td>
<td>15–30 wt%/ 15, 22.5, 30</td>
</tr>
<tr>
<td>Inter electrode gap (IEG)</td>
<td>30–40 mm/30, 35, 40</td>
</tr>
<tr>
<td>Fixed parameters</td>
<td></td>
</tr>
<tr>
<td>Electrolyte</td>
<td>NaOH solution</td>
</tr>
<tr>
<td>Pulse frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Duty ratio</td>
<td>0.5</td>
</tr>
<tr>
<td>Feed mechanism</td>
<td>Automated gravity feed</td>
</tr>
</tbody>
</table>

3  Results and discussion

3.1  Experimental results

Based on the experimental results the second order non-linear models have been established and the influences of various process parameters such as applied voltage ($X_1$), electrolyte concentration ($X_2$) and IEG ($X_3$) on different machining criteria i.e., MRR, overcut (OC) HAZ area and machining depth have been studied. Design of experiment (DOE) features of MINITAB software was utilised to obtain the second order rotatable FCD. Three set of experiments have been conducted at each parametric combination and the average value of results as shown in Table 3 were considered for analyses.

3.2  Development of empirical models for different criteria

A model has been developed to correlate the interaction and higher-order effects of the previously mentioned micro-ECDM process parameters, utilising the relevant experimental data as observed during micro-channel cutting operation. The empirical model for MRR of micro-ECDM has been established and expressed as below:

$$ Y_i (MRR) = -321.4 - 7.07X_1 + 2.246X_2 - 7.52X_3 + 0.0461X_1^2 - 0.04351X_2^2 + 0.0341X_3^2 - 0.01014X_1X_2 + 0.0768X_1X_3 + 0.00919X_2X_3. $$ (2)
Also, the mathematical models for OC, HAZ and machining depth of micro-ECDM have been established and expressed in equations (3)–(5) respectively.

\[
Y_O (OC) = 5539 - 52.1X_1 - 4.23X_2 - 213.5X_3 - 0.097X_1^2 - 0.917X_2^2 + 1.382X_1X_2 + 0.3770X_1X_3 + 1.646X_2X_3 + 0.7335X_1X_2X_3
\]

(3)

\[
Y_H (HAZ) = -8.18047 + 0.515163X_1 - 0.191005X_2 - 0.245419X_3 - 0.00407266X_1^2 + 0.00427499X_2^2 + 0.00470284X_3^2 + 0.00129800X_1X_2 - 0.00165000X_1X_3 - 0.000233333X_2X_3
\]

(4)

\[
Y_M (MD) = -6478 + 273.08X_1 - 34.71X_2 - 28.09X_3 - 2.5124X_1^2 + 0.2856X_2^2 + 0.3918X_1X_2 + 0.3773X_1X_3 + 0.0303X_2X_3 - 0.0196X_1X_2X_3
\]

(5)

These above mathematical models were used to analyse the effects of various process parameters on different machining criteria and to search out the suitable parametric conditions for the best performances.

**Table 3** Experimental results at different parametric combinations

<table>
<thead>
<tr>
<th>Expt. no.</th>
<th>Applied voltage (v)</th>
<th>Electrolyte con. (wt %)</th>
<th>Inter electrode gap (mm)</th>
<th>MRR (mg/h)</th>
<th>OC (µm)</th>
<th>HAZ (mm²)</th>
<th>MD (µm)</th>
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</thead>
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<tr>
<td>1</td>
<td>50</td>
<td>15.0</td>
<td>30</td>
<td>24.46</td>
<td>337.590</td>
<td>0.76125</td>
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<td>2</td>
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<td>30</td>
<td>25.64</td>
<td>275.030</td>
<td>1.10227</td>
<td>299.423</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>30.0</td>
<td>30</td>
<td>24.51</td>
<td>276.916</td>
<td>1.59475</td>
<td>213.346</td>
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<tr>
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<td>25.41</td>
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<td>2.16547</td>
<td>302.984</td>
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<tr>
<td>5</td>
<td>50</td>
<td>15.0</td>
<td>40</td>
<td>11.89</td>
<td>109.413</td>
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</tr>
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<td>189.611</td>
<td>0.97227</td>
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<td>22.32</td>
<td>256.178</td>
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<td>312.987</td>
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</table>
3.3 Analysis of variances (ANOVA) for different machining criteria

The total corrected sum of squares (SS) in ANOVA is used as a measure of overall variability in data. Intuitively, this is reasonable because the sample variance of the Y’s, which is a standard measure of variability, could be obtained if ‘SS’ is divided by an appropriate number of degree of freedom (DOF). The total variability in the data as measured by the total corrected sum of squares (SS) is partitioned into the sum of squares due to factors or parameters (SS_{Factor}) (i.e., between factors) and a sum of squares due to error (SS_{E}) (i.e., within factors). Therefore, the ANOVA provides us with two estimates of $\sigma^2$ – one based on the inherent variability within factors and one based on the variability between factors. If there are no differences in the factor means, these two estimates should be very similar otherwise it is suspected that the observed difference must be caused by differences in the factor means. Then a test of the hypothesis of no difference in factor means can be performed by comparing a mean sum of squares (MSS) due to factors or parameters and due to error. The MSS due to factors and due to error are calculated by dividing the sum of squares due to factors and sum of squares due to error by the number of their respective DOF. Heuristically, MSS due to error (MS_{E}) is an unbiased estimator of $\sigma^2$ and also MSS due to factors (MS_{Factor}) is an unbiased estimator of $\sigma^2$ if there are no differences in the factor means i.e., under the null hypothesis (Montgomery, 1997). But if factor means do differ, the expected value of the factor mean squares is greater than $\sigma^2$.

In the ANOVA of RSM, the mean sum of the squares of the first order terms, second order terms, lack of fit and experimental error evaluated by dividing their sum of squares with their respective DOF. For the value of F-ratio, the mean sum of the squares of lack fit (MS_{L}) is divided by the MSS of experimental error (MS_{E}). The calculated F-ratio is compared with the standard value of F-ratio. If the calculated F-ratio is less than the corresponding standard value of F-ratio for a particular confidence level, then the test will justify the adequacy of the developed mathematical second order model at that confidence level for the chosen parametric consideration and other involved assumptions. Alternatively, the P-value approach is used for decision making.

Therefore, an ANOVA test for P value and F-ratio were performed to justify the goodness of fit of the developed mathematical models. Since the calculated values of F-ratio for the lack of fit is found to be less than the standard F-ratio values (4.06) for (5, 5) DOF for MRR, OC, HAZ and machining depth, it can be ascertained that the second order regression models are adequate and significant at 95% confidence level with 5, 5 degrees of freedom (DOF) to represent the relationship between MRR, OC, HAZ and machining depth with various machining parameters of the micro-ECDM process. Estimated regression coefficients and ANOVA for MRR, OC, HAZ and machining depth suggest that these models adequately fit the data. The values of $R^2$ for MRR, OC, HAZ and machining depth are 97.73%, 98.39%, 95.32% and 98.72% respectively indicating the goodness of the models. Also, the values of adj-$R^2$ for MRR, OC, HAZ and machining depth are very close to $R^2$ indicating the goodness of the models. Hence, the developed mathematical models, which link the various machining parameters with MRR, OC, HAZ and machining depth can adequately be represented through the RSM. The ANOVA tests for MRR, OC, HAZ and machining depth are shown in Table 4.
Table 4
Analysis of variance for MRR, OC, HAZ and machining depth

<table>
<thead>
<tr>
<th>Source</th>
<th>DOF</th>
<th>SS</th>
<th>MSS</th>
<th>F</th>
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3.4 Influences of process parameters on MRR, OC, HAZ and machining depth

The effects of applied voltage, electrolyte concentration and IEG on MRR, OC, HAZ and machining depth during micro-channel cutting on glass are shown in Figures 2–5 respectively. These figures were prepared based on the empirical models represented in equations (2)–(5). The smooth lines in the figures have been drawn on the basis of above equations whereas each dotted line represents the experimental results. From Figures 2–5 it is clear that the trends of dotted lines and smooth lines are almost similar. Therefore, it can be said that experimental results corroborate the developed empirical models outside the ranges already used to develop the models.

From Figure 2, it is observed that MRR increases as electrolyte concentration and applied voltage are increased keeping the IEG fixed at 35 mm. Sparking rate is increased if applied voltage is increased because the current density becomes high under higher voltages. The conductivity of electrolyte increases with the increase of electrolyte concentration, causing a higher rate of bubbles generation and high intensity of sparking. The energy released due to electrochemical discharges under higher voltages and higher electrolyte concentrations is much more and it causes higher material removal. It is also clear from Figure 2(i) and (ii) that MRR increases as electrolyte concentration increases up to 22.5wt%, after that MRR decreases. If electrolyte concentration increases then the solubility of electrolyte decreases and causes lower machining rate in micro-machining operation. Also, the conductivity of NaOH electrolyte solution attains the maximum value near about 22wt% concentration. Figure 2(ii) reveals that MRR decreases with the increase of IEG. The IEG resistance increases with an increment of the gap distance between the tool and the auxiliary electrode. As a result, the rate of sparking decreases since the current flows at a low rate and it reduces the number of nucleation site of bubble generation.

The influences of the applied voltage, inter-electrode gap and electrolyte concentration on OC during micro-channel cutting operation, are observed and exhibited in Figure 3. The nature of variation of overcut with varying applied voltage and electrolyte concentration is comparable with that of MRR with varying applied voltage and electrolyte concentration. Figure 3(i) reveals that the overcut during micro-channel cutting operation increases with the increase of applied voltage. This is because of the fact that under high applied voltage more number of gas bubbles is generated at the sidewall of the tool on account of joule heating of electrolyte due to constriction effect. It may increase the possibility of stray sparking as well as the energy released, which causes larger OC due to higher material removal from the sidewall of micro-channels. From Figures 3(i) and (ii), it is also observed that overcut is maximum at 22.5wt% but thereafter if electrolyte concentration is increased further OC is found to be decreased. Therefore, it implies that the micro-channels become wider up to 22.5wt% of electrolyte concentration on account of higher material removal from the sidewall of micro-channels. Up to 22.5wt% concentration, the electrolyte conductivity enhances the electrochemical reactions, which are responsible for gas bubble generation. Overcut decreases with the increase of IEG since the electrical resistance in the IEG changes with the length of the gap. So, the rate of sparking is reduced not only at the bottom surface of the tool but also at the sidewall of the tool.
The HAZ, which is formed around the outer edge of machining zone due to lack of melting of job material and non-removal of molten material is considered as an undesirable result because cracks are formed in the zone and degrade the quality of products. The variation of HAZ area with varying applied voltage, electrolyte concentration and IEG has been observed and depicted in Figure 4, which shows that HAZ area increases with the increase of applied voltage and electrolyte concentration and a decrease of IEG. Due to an increase of applied voltage and electrolyte concentration and a decrease of IEG, high thermal energy is released by electro-spark discharge phenomenon and conducted to the glass workpiece. But this heat is not sufficient to melt or vaporise completely the material up to which heat is conducted. So, the amount of unmolten material is increased and that causes bigger HAZ area.
Figure 5(i) shows that the machining depth is increased initially with applied voltage up to 55 V then decreases with its increment. Figure 5(i) and (ii) refer that the machining depth is found to decrease with the increase of electrolyte concentration. Therefore, it can be said that the machining depth depends upon the amount of electrolyte available at the machining zone during micro-channel cutting operation. The number of hydrogen bubbles and vapour bubbles are found to be more with the rise of applied voltage and electrolyte concentration as well but these bubbles restrict the flow of electrolyte at the bottom of the tool due to buoyancy force. So, there is a delay in the formation of insulating gas film layer at tool surroundings and it reduces the rate of sparking and also the spark energy. Hence, MRR as well feeding rate are found to be slower and thereby causing a decrease in the machining depth with the increase of applied voltage and electrolyte concentration. From Figure 5(ii), it is evident that the IEG has less effect on machining depth during micro-channel cutting operation on glass. Almost no variation is found in machining depth with a change of the IEG.
3.5 Determination of optimised conditions

In this present investigation, the desired objectives are to get maximum MRR and machining depth and minimum OC and HAZ for cutting good micro-channel on glass. Figures 6(a)–(d) represent the graphical views of single objective optimisation conditions based on RSM (Montgomery, 1997) for maximum MRR and machining depth and minimum OC and HAZ. It is found that maximised MRR is found as 27.60 mg/h at the parametric combination of 60 V/21.9697wt%/30 mm using RSM. Figure 6(b) represents the graphical view of single objective optimisation condition based on RSM for minimum OC and the figure reveals that minimised OC is achieved as 106.4649 µm at 50 V/15wt%/40 mm. Figure 6(c) and (d) inform that the minimised HAZ area of 0.6252 mm² and maximised machining depth of 355.415 µm are obtained at the parametric combination of 50 V/15.7576wt%/35.2525 mm and 55.7576V/15wt%/40 mm respectively according to single-objective optimisation based on RSM. Figure 7 shows the graphical view of multi-objective optimisation for maximum MRR and machining depth and minimum OC and HAZ obtained simultaneously at the parametric combination of 57.9798 V/15wt%/36.7677 mm using RSM. The graphical view represents that MRR, OC, HAZ and machining depth may be attained as 19.9652 mg/h, 180.6409 µm, 0.9113 µm² and 331.3521 µm respectively at the above condition.

The above parametric conditions are obtained theoretically and cannot be set by any instrument due to a fractional value of parameter levels. Therefore, there is an urgent need to use an advanced optimised method, which can nullify the above problem. Also, for better accuracy, the evolutionary optimisation method has been searched out for better-optimised results. There are various evolutionary optimisation methods available today for finding out the optimal results of machining criteria. Genetic algorithms (GAs) have the capability to solve the engineering optimisation problems as a form of complex non-linear problem (Deb, 2000). GA optimises the responses by more and more iterations until the function comes to stop condition. As a result, better-optimised value can be found out and the result represents experimentally validated. So, again optimisation was done based on GA for searching out better-optimised value. 80 chromosomes were generated randomly for better crossover generation and these were the population of involved regeneration crossover. The iteration was continued till the stop condition for \( n = 1000 \) generation was reached during both single-objective optimisation and multi-objective optimisation for MRR, OC, HAZ and machining depth. The probability of crossover and the probability of mutation were taken as 0.8 and 0.05 respectively. Equation (6) represents the minimised function of MRR, OC, HAZ and machining depth based on GA.

\[
\text{So, minimise } F(X_1, X_2, X_3) = 1/\text{MRR} + 1/\text{MD} + \text{OC} + \text{HAZ},
\]

where \( 50 \leq X_1 \leq 60,\ 15 \leq X_2 \leq 30,\ 30 \leq X_3 \leq 40,\) and \( X_1 = \text{Voltage},\ X_2 = \text{Electrolyte concentration and } X_3 = \text{Inter electrode gap}.\)

According to single-objective optimisation, it is found that optimised MRR is 27.5238 mg/h at the parametric combination of 60 V/22wt%/30 mm based on GA. At 50 V/15wt%/40 mm, OC best fitness is achieved as 293.468 µm and the minimised
HAZ area of 0.625219 mm² is attained at the parametric combination of 50 V/15 wt% /35 mm based on GA. It is found that maximised machining depth is achieved as 355.733 µm at 55 V/15 wt% /40 mm. The single-objective optimisations based on GA are shown in Figure 8. Figure 9 exhibits the graphical view of multi-objective optimisation of paretofront-function for maximum MRR and machining depth and minimum OC and HAZ with parametric combination and machining range. The multi-objective responses are found as MRR of 27.5238 mg/h, OC of 293.485 µm, HAZ area of 0.625223 mm² and also machining depth of 355.732 µm at the parametric combination of 55 V/15 wt% /40 mm using GA and these are experimentally validated. Figure 10(a) and (b) show the optical and scanning electron microscope (SEM) images of µ-channels machined by micro-ECDM on glass at the parametric conditions of 58 V/15 wt% /37 mm (close to the parametric combinations 57.9799 V/15 wt% /36.7216 mm) and 55 V/15 wt% /40 mm, respectively. The average overcut, HAZ area and machining depth are measured as 185.585 µm, 0.92538 µm² and 317.125 µm respectively for micro-channels cut at 55 V/15 wt% /37 mm and 205.565 µm, 0.80538 µm² and 310.125 µm respectively for micro-channels cut at 55 V/15 wt% /40 mm. MRR is obtained as 19.13 mg/h and 18.32 mg/h for above two machining conditions respectively. From the SEM images of micro-channel, which is cutting on the glass in micron range at above two machining conditions, it is clear that the HAZ formed in machining zone is free of micro-cracks.

Figure 6 Single-objective optimisations based on RSM for maximum MRR and machining depth and minimum OC and HAZ: (a) maximum MRR; (b) minimum OC; (c) minimum HAZ and (d) maximum machining depth (see online version for colours)
After studying both single and multi-optimised predicted results obtained by using RSM and genetic algorithm (GA), it is very clear that genetic algorithm would be preferable for attaining the maximum MRR whereas RSM would give the better result for minimum overcut in micro-ECDM during micro-channelling. But both the techniques will show the same prediction for minimum HAZ area and maximum machining depth.
Yet, it can be said that genetic algorithm would be the better option for searching out the suitable parametric combination since different levels of parameters for different combinations can be set in the electrochemical discharge micro-machining setup for conducting experiments effortlessly and it will be helpful to the researchers as well as shop floor engineers.

**Figure 9** Multi-objective optimisation based on GA for maximum MRR and machining depth and minimum OC and HAZ: (a) Pareto optimal solution and (b) parameter levels at optimised condition

**Figure 10** Optical and SEM images of μ-channels on glass at (a) 58 V/15wt%/37 mm and (b) 55 V/15wt%/40 mm
4 Conclusions

From the present experimental investigation, it can be concluded that micro-channel can be generated on brittle electrically non-conducting glass successfully in micro-ECDM process by using a thin metal sheet as a tool.

- MRR increases with the increase of applied voltage and electrolyte concentration when NaOH electrolyte is used for micro-channel cutting on glass by the ECDM process. Overcut always increases with the increase of applied voltage but it increases with the increase of concentration up to 22.5wt%.

- HAZ area increases with the increase of applied voltage and electrolyte concentration. It is also clear that applied voltage is the predominant process parameters to influence the formation of HAZ.

- Machining depth depends on the availability of electrolyte in the machining zone. Machining depth increases with applied voltage up to 55 V and decreases of electrolyte concentration. IEG has comparatively the low effect on machining depth.

- The optimal parametric combination for multi-objective optimisation for maximum MRR and machining depth and minimum OC and HAZ is searched out as applied voltage of 55V, electrolyte concentration of 15 wt% and IEG of 40 mm by using genetic algorithms during micro-channel generation on glass.

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References


