Thermal Loading Effect During Machining of Borosilicate Glass Using ECDM Process

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Abstract. Glass has unique properties for micro fluidic, MEMS and optical applications. However, poor machinability of glass materials limit its applications. ECDM process is one of the most utilized micro machining process for fabrication of glass micro products. In ECDM thermal energy of discharges utilizes to provide thermal loading for removal of material. However, controlled thermal loading requires for machining of glass materials owing to its poor thermal conductivity. High thermal stresses may develop at high thermal loading, which leads to uncontrolled facture of glass material. Therefore, a thorough discussion is needed to understand the effect of thermal loading on glass materials. In this study, the experiments are conducted to investigate the thermal loading effect on borosilicate glass during ECDM process. Also, an analytical model is developed to estimate the induced thermal stress during ECDM process. Theses thermal stresses are discussed during drilling of micro hole on work material. After discussion three zones are identified for machining of borosilicate glass using ECDM process, wherein zone-II (i.e. from 44 V to 52 V applied voltage) is identified for safe machining.

1. Introduction

Micro products of glass materials in miniaturization have gained popularity due to its properties like optical transparency, chemical inertness, high hardness and high stability in exposure to sunlight or UV light. MEMS, Lab-on-a-chip, micro fluidics and optical industry are the application area of glass materials [1]. Machining is one of the essential process for fabrication of such products. However, conventional machining of glass material is challenging due to its high hardness, non-conductivity, low thermal conductivity and brittleness. Non-conventional machining processes based on mechanical, chemical, thermal and their hybrid energies have been used for machining of glass materials. Thermal energy based processes are one of the solution to machine these materials. Electrochemical discharge machining (ECDM) process is one of them. The ECDM process can machine nearly all engineering materials irrespective of their properties. The ECDM process includes electrolytic solution, wherein tool electrode (cathode), auxiliary electrode (anode) and work material are immersed. DC power source is used to provide applied voltage to both the electrodes. As the applied voltage increases hydrolysis of electrolytic solution occurs. This results in evolution of H₂ bubbles form tool electrode and O₂ bubbles from auxiliary electrode. The auxiliary electrode has larger surface area, thus the H₂ bubbles easily concentrate around the small surface area of tool electrode and form a gas film. The gas film act as an insulating film, which ceases the current flow in the circuit. This results in generation of high electric field in the gas film. The discharges takes place due to breakdown of gas film under high electric field and produces thermal energy around the tool electrode. This thermal energy utilizes in machining of
work material by melting and vaporization. Also, the thermal energy promotes high temperature chemical etching, which assists the removal of work material. Some research work has been done to effective utilization of the produced thermal energy to enhance the performance of ECDM process. Singh and Dvivedi used textured tool electrode, thereby the discharging was uniformly distributed over the machining surface by increasing the nucleation sites on the textured tool electrode [1]. Arya and Dvivedi improved the discharging phenomena during deep micro hole drilling using ECDM process by quantifying and replenishment of vaporised electrolyte inside the machining zone [2]. Saranya and Sankar reduced the loss of thermal energy from sides of tool electrode by using side insulated tool electrode [3]. Pawariya et al. used sonication of tool electrode and calculated the energy channelization index for effective utilization of sonic energy during electrochemical discharge trepanning process [4]. Few others researchers discussed the material removal mechanism of ECDM process by using finite element modelling [5, 6]. Although, the thermal energy utilization has been improved. But, a detailed investigation on thermal loading effect during machining of glass (by considering glass properties) using ECDM process is not reported in existing literatures. The special properties of glass is an important aspect during machining of glass materials using thermal energy. The material removal rate (MRR) is lower at low thermal energy. However, MRR can be improved by increasing thermal energy, but the consequences are high thermal damage and uncontrolled fracture. Hence, a comprehensive investigation is required to understand the effect of thermal loading during machining of glass materials using ECDM process. Therefore, the present article provides a detailed investigation on thermal loading effect during machining of borosilicate glass using ECDM process. An analytical model was developed to calculate induced thermal stress during ECDM process at different applied voltage. A range of applied voltage (in terms of thermal loading) was identified for machining of borosilicate glass using ECDM process.

2. Material and methods

2.1 Experimental setup

The experimental setup is developed in house at a laboratory scale. Figure 1 is showing the schematic view of fabricated setup of ECDM process. This setup consist of two electrodes (i.e. tool electrode and auxiliary electrode), which are immersed into the electrolyte bath along with the work material.

![Figure 1. Schematic view ECDM facility with hollow tool electrode](image1)

![Figure 2. Schematic view of ECDM model assumed for analysis](image2)

Borosilicate glass is used as a work material. Both the electrodes are connected to the DC power source, where the tool electrode as a cathode and the auxiliary electrode as an anode. A hollow tool electrode of SS 304 material with 500 µm outer diameter and 250 µm inner diameter is used. The hollow tool electrode provides addition discharging edges and it used in previous ECDM works [2, 7]. The auxiliary electrode of a graphite and the size is 8x5x1 cm³ is made used. The tool electrode is mounted on a vertical axis (i.e. Z-axis) and the tip of tool electrode is dipped 1-2 mm into the electrolyte bath. The motion of Z-axis is controlled by using a stepper motor with the help of lead screw. The micro
controller is employed to control the direction and speed of stepper motor. The micro controller is programmed using a personal computer. The work material is placed under beneath the tool electrode tip. The electrolyte solution used in present investigation is formed by 20 %, wt./ Vol. NaOH aqueous solution.

2.2 Analytical modelling
A model of ECDM process was considered to obtain induced thermal stress in the work material during thermal loading. The model includes a borosilicate glass work material and thermal loading zone (where the thermal energy was supplied from a heat source). The zone was assumed just above the glass surface and beneath the hollow tool electrode. The tool electrode has 500 μm outer diameter and 260 μm inner diameter. The schematic view of assumed model is shown in Figure 2.

The assumptions of the model for analysis are as follows:

- It was assumed that the input thermal energy from heat source on interaction plane (i.e. between beneath the tool electrode and above the glass surface) was supplied for small fraction of second (i.e. 6 ms).
- The heat transfer was considered along with the thickness of glass work material.
- The interaction plane was assumed at uniform temperature (i.e. there was no temperature gradient within the plane).
- The model of ECDM process was assumed to be an adiabatic system.
- The model follows Hook’s law and produced stresses were considered to be principle stresses along the interaction plane.
- The glass work material was considered at room temperature (i.e. 32 °C).
- Uniform gas film thickness of 25 μm was assumed around the dipped surface of the hollow tool electrode. Hence, the outer and inner diameter of heat source were 550 μm and 210 μm, respectively.

From the law of conservation of energy;
Net supplied thermal energy to the system = Net thermal energy consumed by the system

= Energy consumed in heating of electrolyte, tool electrode, work material and chemical reactions.

Net supplied thermal energy per unit time ‘Q’ to the work material during ECDM process is given by,

\[ Q = V_a \times I_{avg} \]  \hspace{1cm} (1)

Net supplied thermal energy ‘\( Q_s \)’ in total duration,

\[ Q_s = V_a \times I_{avg} \times t_{on} \]  \hspace{1cm} (2)

where, \( t_{on} \) is total heat supplied time (i.e. 6 ms), \( V_a \) is Applied voltage (40, 44, 48, 52, 56, 60 volts) and \( I_{avg} \) is average current, is given by Jain et al. (1999) [6],

\[ I_{avg} = 0.1009 \times V_a^{0.4815} \times K^{0.3420} \times \phi^{0.3420} \times d^{0.2881} \]  \hspace{1cm} (3)

where, \( V_a \) is applied voltage (40-60 V), \( K \) is electrolyte conductivity (41.1 mho/m), \( \phi \) is diameter of tool electrode (500 μm) and \( d \) depth of immersed tool electrode into the electrolyte (2 mm)

As it reported in literature, maximum part (80-90 %) of input energy consumed by electrolyte owing to high thermal conductivity, tool electrode and chemical reactions [4]. Therefore, in this model the heat consumed by work material was assumed to be 14 % of supplied thermal energy.

Percentage of supplied thermal energy to the work material (\( Q_p \)) = 0.14 \* \( Q_s \)

\[ Q_p = 0.15 \times V_a \times I_{avg} \times t_{on} \]  \hspace{1cm} (4)

By using law of conservation, the ‘\( Q_p \)’ is equal to the thermal energy conducted into the work material ‘\( Q_c \)’. Also, using law of heat conduction, also known as Fourier’s law.

\( Q_c = \text{heat conducted into the work material} \)
\[ Q_c = K \cdot A \cdot \left( \frac{\Delta T}{\Delta L} \right) \]  

(5)

By equating equation 4 and 5,

\[ 0.14 \cdot V_a \cdot I_{\text{avg}} \cdot t_{\text{on}} = \left[ K \cdot A \cdot \left( \frac{\Delta T}{\Delta L} \right) \right] \]

\[ \Delta T = \left[ \left( 0.14 \cdot V_a \cdot I_{\text{avg}} \cdot t_{\text{on}} \right) \cdot \left( \frac{\Delta L}{K \cdot A} \right) \right] \]  

(6)

where, \( \Delta T \) is temperature difference in glass work material

**Table 1.** Process parameters with their nomenclature and their values used in analysis.

| S. N. | Parameters name               | Nomenclature | Values                |
|-------|-------------------------------|--------------|-----------------------|
| 1     | Applied voltage (V)           | \( V_a \)    | 40, 44, 48, 52, 56, 60 |
| 2     | Total heat supplied time (ms) | \( t_{\text{on}} \) | 6                     |
| 3     | Thermal conductivity of borosilicate glass (W/m\(^{-1}\)°C) | \( K \) | 1.2                   |
| 4     | Area of heat supplied on glass surface (m\(^2\)) | \( A \) | 2.03 \( \times 10^{-7} \) |
| 5     | Thickness of work material (m) | \( \Delta L \) | 0.0013                |
| 6     | Poisson ratio of borosilicate glass | \( \mu \) | .2                    |
| 7     | Young’s modulus (GPa)         | \( E \)      | 64                    |
| 8     | Linear coefficient of thermal expansion (°C\(^{-1}\)) | \( \alpha \) | 3.3 \( \times 10^{-6} \) |

Mathematical expressions for the thermal stress is given by,

\[ \sigma_t = \left[ E \cdot \alpha \cdot \nabla T \cdot \left( \frac{1}{(1-\mu)} \right) \right] \]  

(7)

Where, \( \sigma_t \) is induced thermal stress, \( E \) is young’s modulus of work material, \( \alpha \) is linear coefficient of thermal expansion, \( \Delta T \) is temperature difference in glass work material and \( \mu \) poisson ratio of work material.

The value of variables used in Equation 7 are given in Table 1.

2.3 Experimental planning

The experiments were performed using ECDM process to investigate the effect of thermal loading on borosilicate glass work material. Applied voltage was varied at (40, 44, 48, 52, 56 and 60) V to control the thermal loading on glass material. Other process parameters were selected from literature and pilot experiments, all are listed in Table 2. Further, experiments were conducted to analyse the effect of applied voltage during machining of micro holes on work material. The developed analytical model was used to estimate thermal stresses at same values of applied voltage (those were used in experiments). The experimental and analytical model results were discussed to find out the working range of applied voltage during ECDM process.

**Table 2.** Process parameters with their values

| S. N. | Parameters name               | Values                |
|-------|-------------------------------|-----------------------|
| 1     | Applied voltage (V)           | 40, 44, 48, 52, 56, 60 |
| 2     | Electrolyte type / Concentration (%, wt./Vol.) | NaOH / 20 |
| 3     | Thickness of work material (m) | 0.0013                |

3. Results and discussion

The experimenters were conducted to investigate the effect of thermal loading on work material using ECDM process. The thermal loading was controlled by changing the applied voltage at (40, 44, 48, 52, 56 and 60) V during ECDM process. The other parameters were selected from Table 2. The thermal loading was supplied for very short duration 6 ms for all the experiments. Experimental results are plotted in Figure 3. As can be seen the thermal damage on work material increased with increase in
applied voltage. The reason thereof, as the applied voltage increases the thermal loading increases beneath the tool electrode [2]. This results in high thermal damage on work material. It can be also seen from Figure 3 the thermal damage was sharply increased after 52 V applied voltage. The microscopic images in Figure 4 are showing the thermal damage on borosilicate glass with different applied voltages. The thermal damage with micro cracks on work material was almost negligible up to 48 V applied voltage. However, few micro cracks were observed at 52 V applied voltage, but beyond 52 V applied voltage severe thermal damage and micro cracks were observed on glass work material.

![Figure 3. Effect of applied voltage on thermal damage during ECDM process](image1)

![Figure 4. Microscopic images showing thermal damage during ECDM process](image2)

Subsequent experiments were conducted to drilling of micro holes on borosilicate glass to observe the machining behaviour of borosilicate glass material using ECDM process at different applied voltages. MRR was calculate for different value of applied voltages (i.e. 40-60 V, with variation of 4V). The MRR was calculated by measuring the weight different of work material in “mg” (i.e. weight of work material before and after machining) divided by machining time in “min”. The drilling was performed for 1 min. Experimental results are plotted in secondary axis of Figure 5, microscopic images of drilled micro holes are also mentioned. It can be seen that the MRR gradually increased till 44 V and similarly after 52 V, but sharp increase in MRR can be observed from 44 V to 52 V applied voltage. This was because, before 44 V applied voltage the thermal loading effect was very low owing to low thermal energy produced at low applied voltage. However, after 52 V applied voltage the MRR slowly increased, because at higher applied voltage the gas film formation process deteriorated during ECDM process [3]. The effective utilization of thermal loading on work material was observed from 44 V to 52 V applied voltage. The effect can also be observed from microscopic images of drilled micro holes. Negligible micro cracks were observed till 52 V applied voltage, after that the high thermal stress resulted in leading of micro cracks to macro cracks or uncontrolled fracture of work material. Hence, thermal stresses were estimated by using Equation 7 of analytical model and the value of variables are given in the Table 1. Same values of applied voltages as in experiments were used to estimate thermal stresses. The results are plotted in primary axis of Figure 5. As can be seen, during ECDM process the thermal stresses in the work material increased with increase in applied voltage. The reason thereof is increasing the applied voltage increases thermal loading beneath the tool electrode, which results in increase of sudden change in temperature in the localized region. Also, the glass has poor thermal conductivity, hence the heat generated by thermal loading dissipates very slowly and produces thermal stresses in the localized zone. If, the produced thermal stresses are more than its own tensile strength, micro/macro cracks or uncontrolled fracture initiates on the work material [8]. The working range of borosilicate glass were reported 22-32 MPa [9]. Hence, as the value of induced thermal stresses crosses maximum tensile strength of the work material, it may break or fracture at high thermal loading. It can be also seen from Figure 5, negligible cracks on periphery of drilled holes were observer from microscopic image even thermal stresses crossed the minimum tensile strength of work material (i.e. till 52 V applied voltage). The reason thereof was the thermal stresses generated only micro cracks and these cracks helped in material removal by thermal spalling [10]. However, after 52 V applied voltage the high thermal stresses resulted in cracks around the periphery of drilled hole and deteriorated the accuracy. Consequently, three
zones were identified after the above discussion for machining of borosilicate glass using ECDM process. In zone-I the MRR was very low. Zone-II was identified for high MRR with negligible cracks on periphery of drilled micro hole. Thus, this zone was found best for machining of borosilicate glass using ECDM process. However, in zone-III severe thermal damage or micro/macro cracks were observed, because of high thermal stresses induced at high applied voltage.

Figure 5. Effect of applied voltage on thermal stress and MRR during machining of borosilicate glass using ECDM process. Also, microscopic images of drilled micro holes at different applied voltage.

4. Conclusion
Thermal loading was controlled by changing the applied voltage. Their effect on borosilicate glass using ECDM process was investigated by performing experiments for very short period of time. An analytical model was developed for estimation of thermal stresses produced during thermal loading from a heat source at different applied voltage. Further, experiments were conducted to investigate the drilling preference of ECDM process at different applied voltage. The drawn conclusions are as;

- Increase in applied voltage increased the MRR, however the thermal damage and thermal stresses also increased.
- During ECDM the induced thermal stresses helped in material removal up to a certain value of applied voltage (i.e. 52 V) without generating cracks on work material.
- Three zones of applied voltage were identified. Zone-II (i.e. from 44-52 V applied voltage) was found to be the suitable working zone for machining of borosilicate glass using ECDM process.

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