Array microchannels formation in glass workpiece using multi-pass electrochemical discharge milling technique

Dileep Kumar Mishra, Julfekar Arab, Pradeep Dixit*

Indian Institute of Technology Bombay, Powai, Mumbai, India

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Glass Micromachining,
Array Microchannels,
Multi-Pass.

ABSTRACT

In the last two decades, machinability of glass workpiece using electrochemical discharge machining (ECDM) has been widely explored. Microfeatures such as microchannels and microholes in glass workpiece find application in devices pertaining to biomedical and microfluidic fields. The present work reports the fabrication of array microchannels in the glass workpiece using the ECDM process. A multi-pass milling technique was used to create deep channels using stainless steel array tool electrodes and circular ring as anode. Experiments were performed using a pulsed DC power supply and KOH electrolyte (30 % wt.). Effect of the pass numbers i.e. the number of times the array tool electrodes was moved back and forth on the channel depth and width were analyzed. Up to seven passes were used to create straight microchannels and three passes to fabricate spiral-shaped microchannels in the glass workpiece. From the experimental results, it was observed that the microchannel depth and width showed an increasing trend with an increase in the pass number. Optical microscopic images depicted deep microchannels with smooth surfaces were fabricated using the ECDM process.

1. Introduction

Optical transparency, chemical inertness, and biocompatibility nature make glass workpiece a suitable material for biomedical devices. However, machinability of glass workpiece has been a difficult task due to its brittle and hard. Conventionally used contact-based methods such has micro-milling and micro-drilling is not suitable due to the risk of breakage; whereas unconventional methods such as ultrasonic machining, abrasive jet machining, laser machining are expensive or have slow material removal, tool clogging etc.[1]. Therefore alternative method which can create microfeatures in the glass workpiece in an economical and faster way needs to be explored. In the last ten years or so, electrochemical discharge machining (ECDM) has been widely studied in fabricating microchannels and microholes in the glass workpiece. In the ECDM process, the tool electrode having lower dimension is immersed inside the electrolyte and is generally connected to the negative terminal (cathode) while the counter electrode having a relatively larger size (100 times) is connected to the positive terminal (anode) of the power supply. The workpiece is kept very close to the tool electrode (<10 µm) inside the electrolyte. When the applied voltage is increased slowly, electrolysis of the alkaline electrolyte occurs and hydrogen gas and oxygen gas are evolved at the cathode and anode respectively. As the applied voltage is increased, the hydrogen gas density near the cathode increases resulting in formation of a thin gas film. Upon further increase in the voltage, dielectric breakdown of hydrogen gas film occurs and electrochemical discharges are generated. After the discharge, electrons collide with the glass workpiece kept very close to the tool electrode while avalanching towards the anode. Thus high temperature > 5000 K is generated in the local machining zone and material removal occurs by the combined effect of localized melting and vaporization and chemical etching at elevated temperature [2], [3], [4].

Fabrication of microholes and microchannels in glass workpiece using the ECDM process has been reported by several researchers. Zheng et al. [5] demonstrated layer by layer technique to create complex 3D microstructure in a glass workpiece using the ECDM process. Arab et al. used multi-tip array tool electrodes to create through holes silica workpiece using the ECDM process [6]. Han et al. [7] used a textured tool electrode and fabricated a microchannel having a depth of 300 using

*Corresponding author,
E-mail: pradeep.dixit@iitb.ac.in

single-pass ECDM process. Didar et al. studied the effect of machining voltage and reported that the depth of the microchannel increased as the machining voltage was increased [8]. An increase in the overcut and material removal rate (MRR) was observed by Bhattacharya et al. at higher machining voltage and the electrolyte concentration [9]. Arab et al. studied the effect of frequency and duty ratio on MRR and heat-affected zone (HAZ) with 3 ×3 array tool electrode and reported an increase in both MRR and HAZ with the rise in the frequency and duty ratio [10]. Through microchannels were created in 400 µm and 1100 µm thick glass workpiece using ECDM based multi-pass micro-milling technique [11]. Kannojia et al. created through holes by using the ECDM process and later on filled them with copper by electrodeposition technique to make cooper filled TGVs [12].

Overall, very few researchers have demonstrated the fabrication of array microchannels using the ECDM process. Fabrication of array microchannels using array tool electrodes reduces the overall time required for the machining. Therefore, in the present work, fabrication of array microchannels in the glass workpiece using ECDM based multi-pass micro-milling is demonstrated. The effect of the pass number on the channel depth and width was studied.

2. Experimental Details

Simultaneous fabrication of array microchannels requires array tool electrodes. The array tool electrodes were fabricated using Wire-electric discharge machining (W-EDM) as shown in Fig. 1. A thin stainless steel sheet of 350 µm thickness was used as the base material. Depending on the requirement, tool electrodes of a different number of tips were made by the controlled movement of the molybdenum wire along the X-Y axis.

An array tool electrode with five tips is shown in Fig. 2a. The average length of the tool electrode was 12 mm with a tip size of 160 µm (Fig. 2b). These array tools were later on used to create deep microchannels in glass workpiece using the ECDM process.

The ECDM experiments were performed in 1.1 mm thick soda-lime glass workpiece using an in-house built experimental setup (Fig. 3) consisting of a processing chamber, a pulsed DC power supply and 3 axis CNC motion controller. The processing chamber was placed on the X-Y stage and has a workpiece holding vice with a provision for electrolyte circulation through an inlet and an outlet port. The pulse DC power supply had knob arrangements to control the applied voltage, duty cycle and frequency. The array tool electrode (cathode) was mounted to the Z-axis. Accurate movement of the X-Y stage horizontally and Z-axis vertically was obtained by CNC code using the motion controller. A circular steel ring was used as the counter electrode or the anode. An initial gap of 5-10 µm was maintained between the array tool electrode and the glass workpiece using the motion controller for the first pass. For the subsequent passes, the tool electrode was given a vertical downward feed for a distance equal to the channel depth of the previous pass. Pilot experiments were conducted at different applied voltage and tool feed rate to determine the optimum parameter to create array microchannels with smooth profiles. The obtained optimum experimental parameters are listed in Table 1.

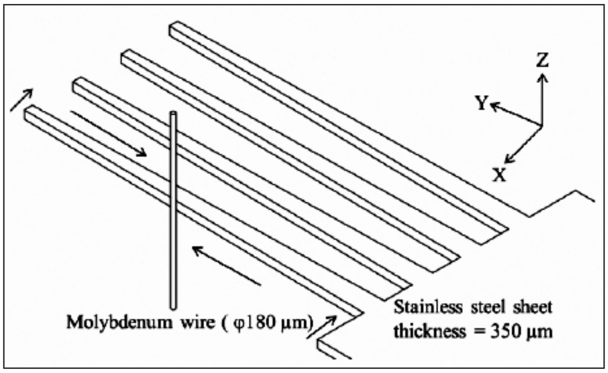

Fig. 1. Fabrication of array tools using W-EDM process.

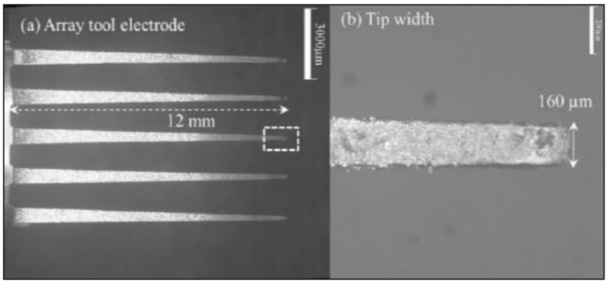

Fig. 2. Tool electrode fabricated using W-EDM process; (a) array tool with 5 tips, (b) Enlarged view of a single tip.

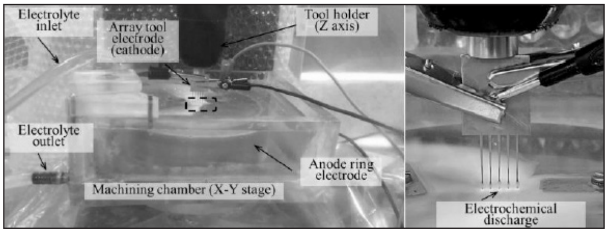

Fig. 3. Image showing various part of the ECDM setup.

3. Results and Discussions

Deep microchannels were created using multi-pass micromilling technique and the channel depth and width were analyzed. The fabricated microchannels cross-section was analyzed under an optical microscope. The depth and width measurements were performed at 3 different locations for each microchannel and the mean value was considered for the analysis.

Fig. 4 shows the V-I curve for the array tool electrode obtained at the specified process parameters. Five different zones were identified in the curve. In the overpotential zone (oa) negligible or no current flow was measured. In the linear zone or ohmic zone (ab) electrolysis started and the measured current increased almost linearly as the voltage was increased. In the limiting current zone (bc), the measure current saturated due to coalesced bubbles covering most of the tool surface. In the instability zone (cd), a thin hydrogen gas film completely isolates the tool surface and current value drops to minimum. Beyond this zone, dielectric breakdown of the gas film occurred and electrochemical discharges were seen around 37 V. Fig. 5 shows the cross-sectional view and width of the microchannel obtained after the 2nd pass. The average channel depth was obtained to be 115 µm while the channel width was 290 µm.

The variation of the depths of the microchannels with different pass number is shown in Fig. 6. Experiments were performed for seven passes to create deep straight microchannels in the glass workpiece. It can be seen that the channel depth increased as the pass number was increased. The average channel depth obtained after the 1st and 3rd were 50 µm and 200 µm, respectively. The channel depth increment was not constant for all the passes. At higher passes, the availability of electrolyte in deep microchannels reduces comparatively resulting in lower electrolysis rate and electrochemical discharge frequency. Therefore, the net material removed decreases. Moreover, due to the reduced electrolyte supply, the flushing efficiency and chemical etching by the heated electrolyte reduce.

Fig. 7 shows the variation of the straight microchannel width obtained after different number of passes. A linear increasing trend in the channel width was observed as the pass number was increased. The channel width was measured to be 270 µm after the 1st pass while the width

Table 1
Experimental parameter data.

Process Parameters	Value
Machining voltage	50 V
Pulse frequency	10 kHz
Electrolyte	30 % KOH (wt. %)
Duty cycle	70 %
Tool immersion depth	1.5 mm
Planer X-Y tool feed rate	25 µm/s
Downwards Z tool feed rate	10 µm/s

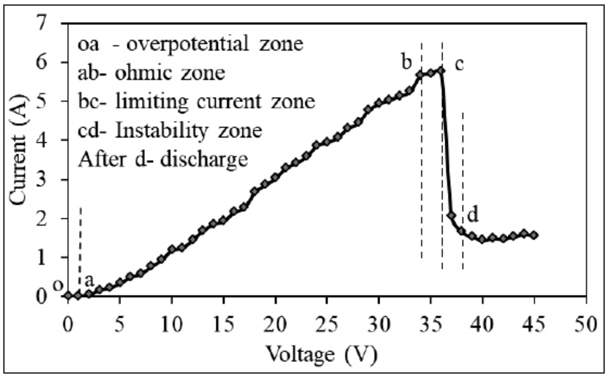

Fig. 4. V–I graph for 5 tip array tool electrode obtained at 50 V, 70 % duty cycle, 10 kHz frequency, and 30 % KOH electrolyte.

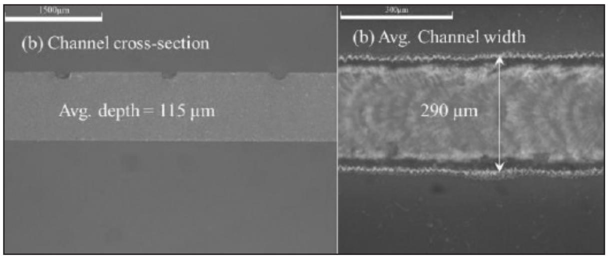

Fig. 5. Optical images showing (a) cross-section view of the channels after 2nd pass, (b) channel width.

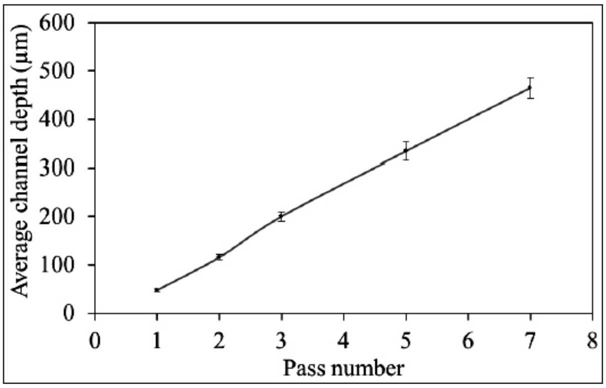

Fig. 6. Variation of average channel depth at different number of pass.

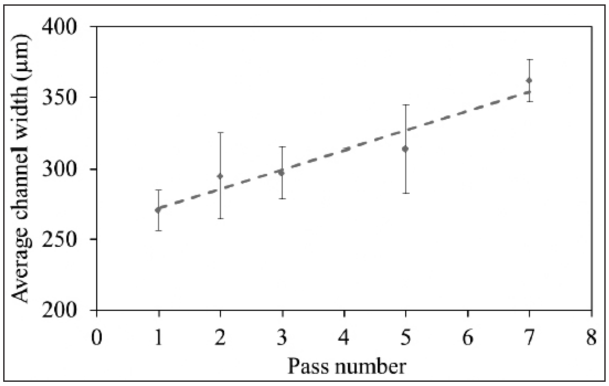

Fig. 7. Variation of channel width at different number of pass.

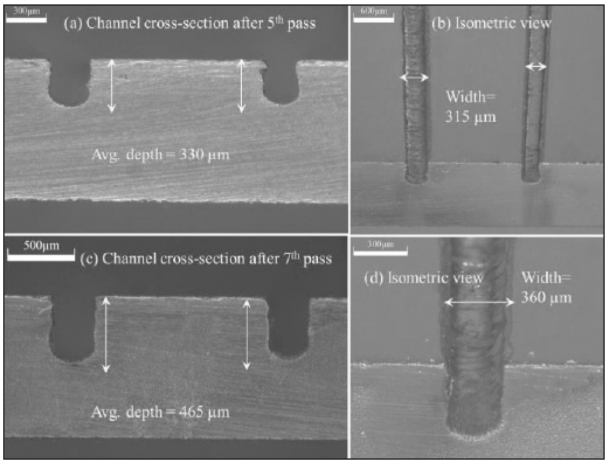

Fig. 8. Images showing a cross-sectional and isometric view of channels obtained after (a, b) 5th pass (c, d) 7th pass.

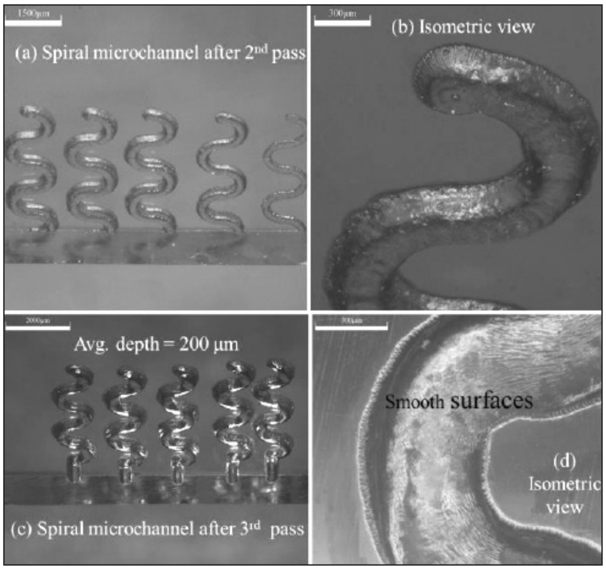

Fig. 9. Optical images spiral microchannels obtained after (a, b) 2nd pass (c, d) 3rd pass.

after 7th pass was 360 µm. As the pass number was increased, the glass-workpiece surface was exposed to electrochemical discharge for a longer duration. Due to this, the channel width and overcut was relatively higher at higher pass number.

Fig. 8 shows the cross-sectional and isometric view of the array microchannels obtained after 5th and 7th pass. The average channel width obtained after 5th and 7th pass were measured to be 315 µm and 465 µm, respectively (Fig. 8b and 8d). Further, heat-affected zone (HAZ) was formed near the edges due to increased electrochemical discharge duration at higher passes. During the ECDM process, tool wear occurs due to collision of the positives ions with tool surfaces. The tool wear was observed to be increasing as the pass number was increased. At higher passes, the electrolyte circulation reduces in reaching the discharge zone, and hence no sufficient cooling occurs resulting in increased tool wear.

Using a similar technique, an array of spiral microchannels were created in the glass workpiece using array tool electrodes (Fig.9). Fig. 9a and 9c show the spiral microchannels obtained after the 2nd and 3rd pass, respectively. The average channel depth obtained after the 3rd pass was 200 µm. From Fig. 9b and 9d, it can be observed that surfaces of the microchannels were relatively smooth due to the chemical etching action of the heated electrolyte during the pulse-off time.

Hence using this multi-pass ECDM based micromilling technique both straight as well shaped array microchannels were created at a very high feed rate of >25 µm/s. The multi-pass technique results in deeper. Buried redistribution lines (RDLs) required in the MEMS packaging applications can also be created using this technique which can be later filled with conductive copper layer.

4. Conclusions

Fabrication of array microchannels using multi-pass based ECDM milling technique was investigated. Experiments were conducted to analyze the effect was process parameters on the microchannel width and depth. From the results obtained thereof, the following conclusions were made:

1. The channel depth and width increased as the pass number was increased.
2. Spiral microchannels with relatively smooth surfaces were fabricated using array tool electrode.

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6. References

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Dileep Kumar Mishra is a Ph.D research scholar in the Mechanical Engineering Department at Indian Institute of Technology Bombay (IITB). He is currently working on experimental and numerical study of micromachining of non-conducting materials using electrochemical discharge machining. He is a graduate in mechanical engineering from Vellore institute of Technology, Chennai campus in 2014. He completed his post-graduation in production engineering from National Institute of Technology Rourkela in 2017. His interest area includes machining of conducting and non-conducting materials using unconventional machining processes

Julfekar Arab is a senior Ph.D. research scholar in the Mechanical Engineering Department at Indian Institute of Technology Bombay (IITB) and currently working in the field of Electro-chemical discharge machining of glass and fused silica for MEMS application. He completed his M. Tech in Manufacturing Engineering from Dr. B.A.T.U., Maharashtra (2015). His Ph.D research work involves investigation into fabrication of single and multiple micro-holes with customized tool electrodes. His research interest is in the Electrochemical Discharge Machining.

Dr. Pradeep Dixit is an Assistant Professor in Mechanical Engineering Department, Indian Institute of Technology Bombay (IITB), India. He received his Ph.D degree from the Nanyang Technological University, Singapore in 2008. He spent one year as postdoctoral researcher in Packaging Research Center, Georgia Tech, USA. Prior to joining IIT Bombay Pradeep worked in Technical Research Centre of Finland (VTT), where he was responsible for the development of 3D interconnect technology and Microsystem packaging. His current research interest lies in the domain of MEMS fabrication, 3D Packaging, and micromachining of difficult-to-machine materials.