Improvement of Surface Quality and Machining Depth of μ-ECDM Performances Using Mixed Electrolyte at Different Polarity

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Abstract
Complex profile and micro-channel generation in silica glass with higher machining depth is an exigent issue to the researchers by μ-ECDM process. Fundamentals of μ-ECDM come from hybrid amalgamation effects of ECM and EDM. The intensity of sparking contributes to material erosion melting and chemical etching of the job-specimen. The paper consists of parametric influences as well as comparative analysis on machining depth (MD) and surface roughness (Ra) using NaOH and KOH at the ratio of 1:0, 3:1, 1:1, 1:3 and 0:1 with varying concentration(wt.%), applied voltage (V), pulse frequency(Hz) and duty ratio (%) in straight as well as in reverse polarity during micro-channel fabrication on silica glass. Different shapes of micro-channel like Zig-Zag, ‘Y’ shaped have been fabricated on silica glass by μ-ECDM process for utilization as a micro-fluidic device using automated spring feed and CAM-follower guided stainless steel (SS) micro-tool. The SEM analysis has been performed to identify the micro-crack and uncut debris into micro-channel. It is found that machining depth has been increased up to 1850 μm with better surface quality using mixed electrolyte of NaOH:KOH::3:1 at direct polarity and also lower TEWR is found using NaOH:KOH::1:3 as electrolyte at reverse polarity.

Keywords μ-ECDM · Machining depth · Surface roughness (Ra) · TEWR · ‘Zig-Zag’ · ‘Y’ shaped · Mixed electrolyte · Polarity

1 Introduction

The production of miniature parts and various shape of micro-profile by electrochemical discharge micro-machining process (μ-ECDM) draw challenging attention to the researchers. Fundamentals of the spark generation and material removal mechanism of ECDM process depended on the twisting effects of ECM and EDM [1, 2]. Surface texture of the job specimen was exaggerated by applied voltage and electrolyte conductivity during ECDM process [3]. Material removal rate (MRR), Heat affected zone (HAZ) and overcut (OC) during micro-drilling on non-conducting materials depended on voltage as well as electrolyte conductivity [4]. The surface roughness (SR) amplified if duty ratio is increased but opposite action of pulse frequency appeared during micro-drilling by ECDM [5]. EPD-grinding could be used to improve surface roughness of micro holes [6]. The quality of machining criteria influenced by applied voltage and electrolyte concentration during micro-machining of advanced ceramics as well as glass by ECDM process [7] and machining performance also depended on inductance, resistance and capacitance of the power circuit of ECDM process [8]. Ultrasonic-vibration improved the geometric configuration of electrochemical discharge micro-drilling performances [9]. Magnetic field also enhanced the machining efficiency and accuracy of ECDM process [10]. Machining depth up to 150 μm reached during ECDM performances [11]. Tungsten carbide (WC) had least tool wear rate (TWR)
during ECDM process due to its higher melting point [12]. Micro-holes on brittle materials could be processed by ECDM [13]. Micro-grinding using polycrystalline diamond (PCD) tools improved the surface quality micro-channel as well as reduced thermal effect [14]. Pulse duration affected on aspect ratio of job specimen during ECDM process [15]. Magnetic field and mixed electrolyte (NaOH+KOH) also augmented machining depth during the ECDM process [16]. Dynamic cylindrical micro-tool electrode improved the performance characteristics of ECDM process [17]. Tool surface temperature at high voltage caused higher tool wear rate [18]. Pulse frequency (f) and duty ratio had domain power to cause higher width of cut like applied voltage [19]. Micro-channel on quartz of 4 mm thickness fabricated using WC micro-tool and achieved better surface texture [20]. Pulse on time and stand-off distance had capability to produce more hydrogen bubbles around the micro-tool during micro-ECDM process [21]. Developed mathematical models of MRR and taper could be highly predicted using artificial neural network (ANN) during machining of silicon carbide by ECDM process [22]. Finite Element Model (FEM) also one of the best fitted technique to predict machining-criteria during micro-machining of borosilicate glass using ECDM process [23]. The desirability function analysis could be used for optimizing MRR and minimization of TWR and NTC [24]. Flow of electrolyte in the machining chamber of ECDM process decreased machining duration by 7 times and enhances the machining accuracy during fabrication of micro holes [25]. KOH was the better electrolyte than NaOH and provided less OC and good hole circularity and observed continuous spark pattern [26]. The recast layers could be vanished using abrasive-grinding micro-tool during ECDM process [27].

Hence, from the literature survey it is clear that different researchers and scientist have carried out performances to fulfill their target but a vital attention can be drawn out to fabricate different shape of micro-channel on silica glass by ECDM process for utilization as a micro-fluidic device as well as for lab on chips. This paper includes the parametric analysis using an indigenously advanced μ-ECDM system which consists automated spring feed arrangement with cam-follower based tool guided unit for generation of different shapes of micro-channel like Zig-Zag, ‘Y’ shaped on glass. The paper search out the basic experimental investigations of parametric influences as well as comparative analysis of different process parameters for Machining Depth (MD) and Surface Roughness (Rₐ) using various mixed electrolyte of different weight proportion like NaOH:KOH:: 1:0, NaOH:KOH::0:1, NaOH:KOH::1:1, NaOH:KOH::3:1 and NaOH:KOH::1:3 to improve surface quality and increase machining depth during micro-channelling on silica glass by micro-ECDM process.

2 Experimental μ-ECDM Set up

To commence the objectives of this research work and to control the process parameters micro-ECDM set-up was designed and developed in the laboratory. Micro-ECDM has three main sub- systems which are mechanical hardware system, electrolyte supply system and electrical power supply unit. Figure 1 shows the developed μ-ECDM system with (a) electrical power system, (b) machining chamber, (c) spring feeding system and (d) CAM-follower tool guiding unit.

3 Experimental Planning

To investigate the influences of process variables like voltage, concentration of electrolyte(wt%), duty ratio(%), pulse frequency(Hz) etc. on machining depth (MD) and surface roughness (SR) (Rₐ) using with the help of spring feed mechanism by using a cylindrical shaped stainless steel tool of diameter 200 μm and mixture electrolyte solution of NaOH and KOH at the ratio of 1:0, 0:1,1:1, 3:1 and 1:3 ratio are used for experimentation. Voltage (35-55v), electrolyte concentration(10-30 wt%), pulse frequency (200-1000 Hz) and duty ratio (45-65%), inter-electrode gap (IEG) 40 mm and stand-off distance (SOD) 0.5 mm have been well thought-out during micro-channelling operation on glass. For better quality of micro-channel surface as well as to reduce side sparking, new micro-tool is used for each experiment during ECDM process.

3.1 Experimental Results and Discussion

Each experiment was conducted three times at every set of machining parametric combination and graphical plots are done individual input-output steps for analysis of effects and comparative study of mixed electrolyte at different proportion.

3.1.1 Influences of Process Parameters and Comparative Studies of Machining Depth (MD)

The comparison of the machining depth (MD) using five different electrolytes NaOH:KOH:: 1:0, NaOH:KOH::0:1 and mixture of NaOH:KOH::1:1, NaOH:KOH::3:1 and NaOH:KOH::1:3 with varying concentrations and voltage change, duty ratio change and varying of pulse frequency has been shown in Fig. 2(a) - (d). From the Fig. 2(a) it is reported that NaOH:KOH::3:1 provides the highest machining depth and NaOH:KOH::1:1 gives lower machining depth respect to other type of electrolyte at any voltage. Machining depth become maximum at 50 V because of continuous
sparking and better quality of film and after that machining depth decreases due to lack of electrolyte on the tool tip. From the Fig. 2(b) it is imaged that machining depth is lower at 10-15 wt% of NaOH:KOH::1:1 and highest at 30 wt% of NaOH:KOH::1:3 because conductivity is enhanced and unremitting sparking occurs when electrolyte concentration is varied from 10 to 30 wt%. From the Fig. 2(c) MD is higher at 60% of duty ratio for any type of electrolyte when duty ratio is varied and other parameters are fixed. It is clear that applied voltage as well as electrolyte concentration plays important rolls to swell machining depth because of rising of conductivity and sparking rate. From the Fig. 2(d) it is illustrated that machining depth become higher at lower pulse frequency and become higher when NaOH:KOH::3:1 is used as electrolyte during varying pulse frequency, keeping other parameter constant at 35v/40%/

![Diagram of μ-ECDM Experimental set-up](image-url)
IEG 40 mm and lower at NaOH:KOH::1:1. Machining depth decreases when pulse frequency increases because current density decreases. As a result machining rate decreases, i.e. material removal decreases and machining depth decreases. When NaOH and KOH is mixed then their dipole moment reduces and accumulation of hydrogen bubble on tool tip increases because conductivity increases and rate of electrolysis is enhanced, so as applied voltage cross the threshold voltage and increases rate of sparking.

3.1.2 Influences of Process Parameters and Comparative Studies on Surface Roughness ($R_a$)

The comparison of the surface roughness (SR) using five different electrolytes NaOH:KOH:: 1:0, NaOH:KOH::0:1 and mixture of NaOH:KOH::1:1, NaOH:KOH::3:1 and NaOH:KOH::1:3 with varying concentrations and voltage change, duty ratio change and varying of pulse frequency has been shown in Fig. 3(a) - (d), when one parameter is varying, other parameters remaining fixed. It is found that surface finish of microchannel is better when NaOH:KOH::3:1 is used as electrolyte and surface roughness is augmented as increase of applied voltage at other parameters are unaltered, Fig. 3(a) represents. At 35 V surface roughness is higher in case of NaOH:KOH::1:3 and lower for NaOH:KOH::3:1. At 50 V, continuous sparking occurs that causes better surface finish in to the channel. Therefore the surface smoothness deteriorates due to thermal effects when NaOH:KOH::0:1 is used at higher voltage and becomes more at 55 V. From the Fig. 3(b) it is observed that NaOH:KOH::3:1 provides lower surface roughness and NaOH:KOH::1:3 gives continuous surface finish when electrolyte concentration is increased up to 25 wt% and surface texture become greater when NaOH:KOH::0:1 is used as electrolyte with 30 wt% concentration. From the Fig. 3(c) it can obviously announced that surface smoothness is decreased when duty ratio is increased, due to higher sparking thermal damage occurred and irregularities in to the micro-channel increases. At 55% duty ratio/10 wt%/200 Hz/IEG 40 mm
Surface finish is better in case of all types of electrolyte and at 45% duty ratio surface roughness is lower for NaOH:KOH::3:1 and higher at 65% duty ratio that causes violent sparking when NaOH:KOH::0:1 is used. From the Fig. 3(d) it can be explained that surface roughness is continuous up to 600 Hz and after that increasing pulse frequency surface roughness become higher because of discontinuous discharge and side stray of sparking. It is clear that at 200 Hz surface roughness is lower when NaOH:KOH::3:1 is used as electrolyte and higher at 1 KHz in case of NaOH:KOH::0:1. NaOH:KOH::3:1 is better electrolyte for better surface finish of silica glass microchannel. Figure 4 show the graphical plot of roughness (Ra) of the surface of micro-channel fabricated on silica glass, machined at different parametric combination like 50 V/25wt%NaOH:KOH:: 1:0/55%/600 Hz, 35 V/15wt%NaOH:KOH::3:1/50%/600 Hz and 50 V/15wt%NaOH:KOH::0:1/350%/400 Hz.

3.2 Comparative Studies on Machining Depth (MD), Surface Roughness (Ra) and Tool Electrode Wear Rate (TEWR) Using Different Electrolyte and Polarity

Total fifteen experiments have been conducted with different polarities for five different electrolytes mixtures i.e., NaOH and KOH are mixed at the ratio of 1:0, 3:1, 1:1, 1:3 and 0:1, by fixing the electrolyte concentration at 10 wt% and other process parameters viz. applied voltage, type of electrolyte; pulse frequency, inter-electrode gap and duty ratio. Figure 5(a), (b) and (c) show the schematic diagrams

![Fig. 3 a-d Comparative study of surface roughness using mixed electrolyte. a Effect of applied voltage on Ra, b Effect of electrolyte concentration on Ra, c Effect of duty ratio on Ra, d Effect of pulse frequency on Ra](image-url)
of direct polarity, reverse polarity and sparking at tool tip of micro-tool in μ-ECDM process.

3.2.1 Effect of Polarity on Machining Depth (MD)

In the present work, the machining depth has been compared for both polarities i.e. direct and reverse in five different mixtures of electrolyte solutions and exhibits in Fig. 6. The Fig. 6 clearly indicates that in case of reversed polarity the machining depth is obtained low because machining rate is low due to low sparking rate. It is found that for reversed polarity as well as direct polarity the 50-50% mixture of electrolytes provides lower machining depth. But 3:1 ratio of NaOH and KOH electrolyte mixtures provides higher machining depth (MD) at direct polarity during micro-channel fabrication on silica glass because at this mixture electrolyte conductivity increases and sparking rate becomes higher at direct polarity than reverse polarity. The discrepancy of
machining depth is found as usual for both polarities in five different mixtures.

### 3.2.2 Effect of Polarity on Surface Roughness ($R_a$)

Figure 7 exhibits the effects of polarities of D.C. power supply on surface roughness for different mixtures of electrolyte. It can also be notice from the Fig. 8 that good surface finish can be achieved by using direct polarity rather than reverse polarity. In direct polarity uniform sparking rate is high whereas in revered polarity uniform sparking rate is comparatively low. There is a tendency to stray around the cutting zone; as a result irregularities are formed on the machining zone and the value of surface roughness becomes higher. From this observation it can be predicted that direct polarity is better than reverse polarity in case of surface texture of machined zone of the job specimen. From the Fig. 7 it is found that at 10 wt% of electrolyte mixture at the ratio 0:1 solution gives more irregular surface and causes higher surface roughness at reversed polarity because of low formation of positive hydrogen bubble, whereas the ratio of 3:1 provides lower surface roughness in case of reverse polarity also. For direct polarity the ratio of 1:3 of NaOH and KOH provides higher surface roughness comparatively to other types and lower for the ratio of 3:1 because continuous discharge occurs and rate of side sparking reduces, so as thermal damage and uncut debris formation reduces.

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**Fig. 6** Effect of polarities on Machining Depth

**Fig. 7** Effect of polarities on Surface Roughness

**Fig. 8** Effect of polarities on Tool Electrode Wear Rate (TEWR)
3.2.3 Effect of Polarity on Tool Electrode Wear Rate (TEWR)

Tool electrode wear rate has been compared for both polarities i.e. direct and reverse in five different types of electrolyte mixture i.e., NaOH and KOH are mixed at the ratio of 1:0, 3:1, 1:1, 1:3 and 0:1 and are shown in Fig. 8. It is observed from Fig. 9 that more tool electrode wear rate is occurred in case of direct polarity compared to the reverse polarity. In direct polarity sparking rate is high compared to that in reversed polarity and higher temperature raises in the cutting zone, as a results more tool wear is occurred in case of direct or straight polarity. It is found that more tool wear rate is occurred due to higher rate of sparking at direct polarity with 10 wt% of 0:1 ratio of NaOH and KOH electrolyte mixture and 1:3 ratio provides lower tool wear rate for both direct and reverse polarity. The tool wear rate initially starts at 45 V for stainless steel micro-tool for direct as well as reverse polarity during micro-machining by ECDM process. Tool wear rate is found low in case of mixed electrolyte compared to NaOH and KOH electrolyte. But increasing of material removal rate is the main target, so direct polarity is the best polarity for the micro-fabrication of silica glass. SEM images of micro-channel of silica glass are exhibited in Fig. 9 using various electrolyte solutions and at different machining conditions.

4 Conclusions

From the present parametric analysis and comparative study using different electrolyte and tool polarity change during μ-channel cutting operation on silica glass by advanced micro-ECDM process, the present set of research following outcome drawn out-.

i. Electrochemical discharge micro-machining (ECDM) system successfully design, fabricated and developed for different shapes of μ-channel as well as micro-profile cutting on electrically non-conducting material like silica glass.

ii. Machining depth as well as surface roughness increases by escalating of voltage, duty ratio and electrolyte concentration but after 55 V and 60% of duty ratio machining depth decreases. Pulse frequency is inversely proportionate with machining depth and achieved better machining depth at 600 Hz but less effect on surface roughness.

iii. At 50 V and 25 wt% sparking is continuous, so enhanced surface finish can be found and 400-600 Hz pulse frequency.

![SEM of Micro-channel of glass at 50V/15wt%NaOH:KOH::1:3/200Hz/45% with reverse polarity](image1)

![SEM of Micro-channel of glass at 50V/10wt%NaOH:KOH::3:1/200Hz/45%](image2)

‘Y’ Shaped micro-channel cutting at 50V/10wt%NaOH:KOH::3:1 /200Hz/45%

Zig-Zag’ micro-channel cutting on glass at 50V/10wt%NaOH:KOH::3:1 /200Hz/45%

![Fig. 9 Different shapes of micro-channels cutting at different conditions on silica glass by μ-ECDM process](image3)
iv. Surface becomes rough due to the thermal effects in the machining zone when NaOH:KOH::0:1 is used at 55 V and 30 wt%. NaOH:KOH::3:1provides lower surface roughness and NaOH:KOH::1:3gives continuous surface finish when electrolyte concentration is increased up to 25 wt%.

v. It is found that more tool wear rate occurred due to higher rate of sparking at direct polarity with 10 wt% of NaOH:KOH::0:01 electrolyte solution and NaOH:KOH::1:3 provides lower tool wear rate at reverse polarity and if tool wear occurs, surface roughness raises.

vi. ‘Y’ shape, as well as ‘Zig-Zag’ shape has been cut at 50 V/10wt%NaOH:KOH::3:1200 Hz/45% with machining depth of 1850 μm on silica glass.

vii. Miro-channel of silica glass can be used for micro-reactor applications, MEMS and micro-fluidic devices or lab-on-chips.

viii. Some limitations of the system also observed during experimentation, such as difficulty to control machining depth rate (MDR).

ix. It is observed from Scanning Electron Microscopy (SEM) images that surface texture of μ-channel on glass varies with different process parameters and micro-crack are observed in direct as well as reverse polarity. But more micro-crack is formed for reverse polarity. From SEM analysis of micro-channel little debris are found and thermal effect is clearly observed.

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