On electrochemical discharge milling of glass with horizontal tool and vertically upward feeding technique

Sudip Santra*, **Biplab Ranjan Sarkar, Biswanath Doloi, Bijoy Bhattacharyya**

Jadavpur University, Kolkata, India

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ABSTRACT

KEYWORDS

ECD Milling,
Vertically Upward Feeding,
MRR,
Overcut,
Glass.

Electrochemical Discharge Milling (ECD milling) process encounters some problems like the uneven edge of the machined channel, lower machining depth, uncontrollable spark discharge, etc. The primary cause of those issues is a lack of gas bubbles in the machining area, which are necessary for good spark discharges. Due to the buoyancy of the liquid, gas bubbles cannot remain at the tool-electrode tip and poor flushing arises from feeding the tool-electrode on the top surface of the workpiece. In this study, horizontal tool-electrode and vertically upward feeding technique has been introduced to solve the problems that arise during the existing feeding technique. The material removal rate (MRR) and overcut during ECD milling are observed and analysed by changing the applied voltage, concentration of electrolyte and feed rate of tool. MRR and overcut are found as 5.025µg/min and 116.86µm respectively at 40V, 20wt% concentration of electrolyte and 50µm/sec of feed rate.

1. Introduction

A promising machining technique for removing components from electrically non-conductive materials is electrochemical discharge milling that have varieties of uses in MEMS, bio medical device, lab-on-chip devices etc. Two types of electrochemical reactions are occurred at the cathode, where hydrogen bubbles are generated, and at the anode, where oxygen gas is generated. Together, the hydrogen gas bubbles and the vapour bubbles that congregate around the tool electrode create an insulated gas sheet over its exposed surface (Bhattacharyya et al., 1999). This layer of gas film ruptures at a certain voltage, causing a spark discharge between the cathode tool-tip and electrolyte. The heat developed due to the spark discharges removes materials from the workpiece by causing it to melt and vaporize when the workpiece is placed close to the sparking zone. According to several studies, spark discharged heat often exceeds the glass melting temperature and approaches the glass vaporization temperature (Basak & Ghosh, 1997; AbouZiki et al., 2012). Additional studies have revealed that high-temperature chemical etching also causes the loss of components from the glass surface (Jain & Adhikary, 2008). According to Wüthrich et al. (2006), the current signal can be used to monitor the electrolyte temperature and the existence or absence of a gas film during ECDM. MRR grew twice as rapidly with ultrasonic vibration applied as compared to without vibration (Elhami & Razfar, 2017). The quantity of material removed increased when ultrasonic vibration was applied with a 10 µm amplitude compared to when it wasn't used (Elhami & Razfar, 2018). However, a big amplitude reduced the vibration's impact. MHD convection was produced by introducing a magnetic field to the system, enabling electrolytes to travel through the machining region and increasing the frequency of sparks, which increased MRR (Ratan & Mulik, 2017; Xu & Jiang, 2021). The $(OH)^{-}$ ion concentration increased with the electrolyte's reduced surface tension, which led to a thinner gas layer and enhanced surface quality during surface machining (AbouZiki et al., 2012; Yang et al., 2010). The larger tool-to-workpiece gap enables the discharge to impact the workpiece with greater kinetic energy, causing the machined surface to be rougher and encouraging cracking. Maintaining an optimal tool-workpiece distance was important to provide a proper machined profile (Torabi & Razfar, 2021;

*Corresponding author E-mail: sudip16santra@gmail.com

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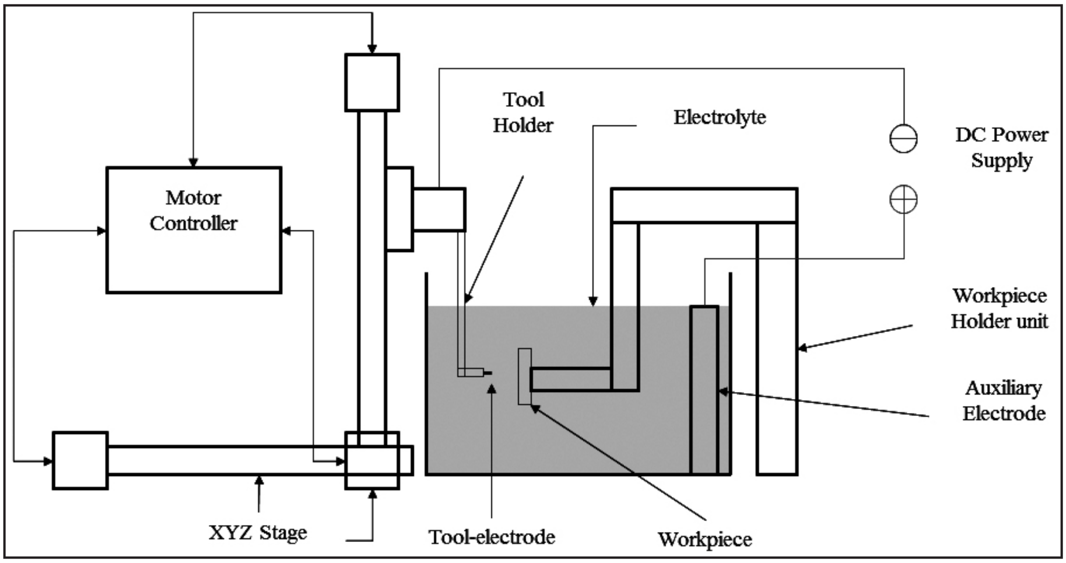

Fig. 1. Schematic diagram of the in-house developed experimental setup.

Arab et al., 2021). In micro-drilling of silicon nitride and glass, Sarkar et al. (Sarkar et al., 2006; Sarkar et al., 2009) demonstrated that the IEG had the least impact on MRR, ROC, and HAZ area. Santra et al. (Santra et al., 2022) compared three different kind of tool feeding technique and found the side feeding as the best appropriate feeding technique in ECD milling.

By including new characteristics or mechanisms in the fundamental machining setup, such as tool-electrode vibration, the inclusion of a magnetic field, etc., research has been done to enhance the machining performance of ECD milling. This paper describes the use of horizontal tool-electrode and vertically upward feeding technique to increase MRR and decrease overcut. The vertically upward feeding technique that is used during ECD milling can ease the release of machined products due to gravity and flow of fresh electrolyte along with accumulation of bubbles continuously at the machining zone and.

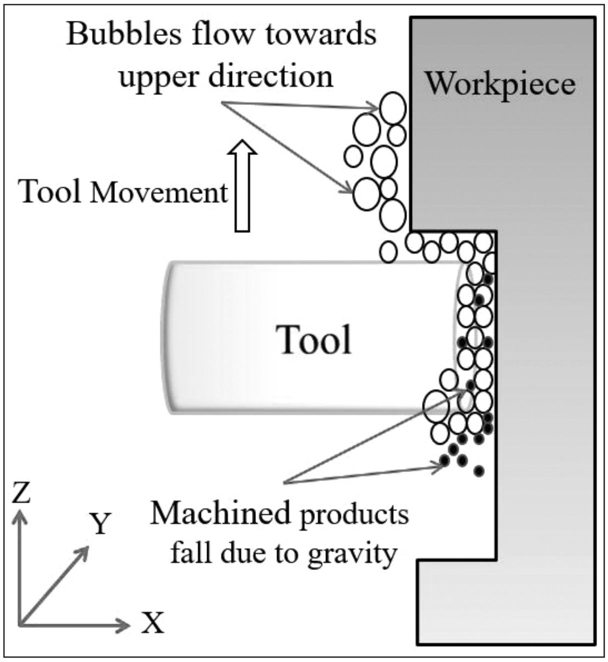

Fig. 2. Schematic representation of bubble flow during vertically upward feeding.

2. Experimentation

2.1. Experimental setup design

The experiments were conducted with the help of an in-house developed ECD milling setup. The setup consists of an X-Y-Z stage, machining chamber, power supply, motor controller, tool and workpiece holder, etc. X-Y-Z stage is movable in three directions among which the Z-axis direction can move the tool-electrode vertically whereas the X-axis direction is used for depth feeding. DC power supply was utilized to give a potential difference between the tool-electrode and the auxiliary electrode. The detailed schematic diagram of the indigenously developed setup and flow of bubbles are given in Fig.1 & 2.

Tool-electrode holder was attached with the z-axis that can hold and move the tool upward and downward direction vertically according to the given command. A solid cylindrical copper tool of 500µm diameter was used during the milling process on the glass slide workpiece. The machining was done under the aqueous sodium hydroxide solution, which acted as an electrolyte.

2.2. Method of machining

A novel tool-electrode feeding technique is introduced during this study to increase the MRR and decrease the overcut of the machined channel. In this study, the tool-electrode and the workpiece were oriented in such a way that the tool-electrode remain perpendicular horizontally to the z-axis and the feeding could be given in an upward direction as depicted in Fig.1. Concentration of electrolyte, tool feed rate, and applied voltage were regulated to observe the change of MRR and the overcut accordingly. One factor at a time (OFAT) method was applied to notice specifically MRR and Overcut. The experimental parameters that were used during machining were given in Table 1.

The weight of workpiece sample was taken before machining and compared with its weight after machining to estimate the MRR.

Table 1
Experimental parameters.

Items	Details
Workpiece	Glass slide
Tool-electrode material	Copper
Tool-electrode diameter	500µm
Auxiliary electrode material	Graphite
Electrolyte	Aqueous NaOH
Power Supply	Constant DC
Concentration of electrolyte (wt%)	15, 20, 25
Feed rate of tool (µm/sec)	40, 50, 60, 70
Inter-electrode gap (IEG) between anode and cathode	100mm

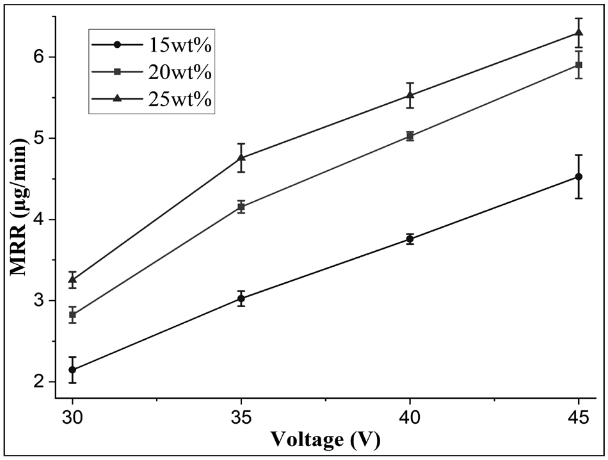

Fig. 3. Effects of voltage on MRR at different concentrations of electrolyte.

3. Results and Discussion

3.1. Influence of applied voltage on MRR and overcut

Mainly, the material from the glass surface is removed due to thermal energy. Although, the material removal mechanism is very complex in the case of electrochemical discharge milling. However, the thermal energy at the machining zone depends on the intensity of spark discharges and their effectiveness to remove materials. The effectiveness to remove materials is referred to as how much energy of spark discharge is responsible to melt and vaporize glass material. From the experiments, it was found that the applied voltage was the most influential parameter to alter the MRR. An increase in the potential difference between tool-electrode and auxiliary electrode increases the rate of electrolysis which produces more amount of hydrogen gases at the cathode. The presence of sufficient gas bubbles at the machining zone generates spark discharge frequently. According to the mechanism of spark discharge, the generated gas bubbles merged into each other and produce an insulating gas film around the tool-electrode which disconnects the current flow from the tool-electrode to the electrolyte. This gas film breaks down with a high-intensity spark discharge when the voltage is higher. MRR was 6.297µg/min at 45V and lower at 30V as shown in Fig.3.

It is also noticeable that the deviation of MRR was more at higher voltage due to uncontrollable spark discharges. The high-intensity spark discharge creates a larger crater on the glass surface and removes more amount of material than the lower potential difference. The energy of spark discharge is not fully used to remove materials from the workpiece because the spark discharge spread around all possible directions. That deviated spark discharge is responsible for overcut which is 373.62µm at 45V and 43.74 µm at 30V as shown in Fig.4.

The overcut was increased gradually up to 35V and after that, it was increased rapidly from 40V to 45V. The deviation of overcut depends on the density of the spark discharge and it is lower at 40V due to controlled discharge and evenly removal of materials from the workpiece. In the case of the vertically upward feeding technique, the discharge area at the machining zone is more than the usual feeding technique and removes more amount of material from the workpiece.

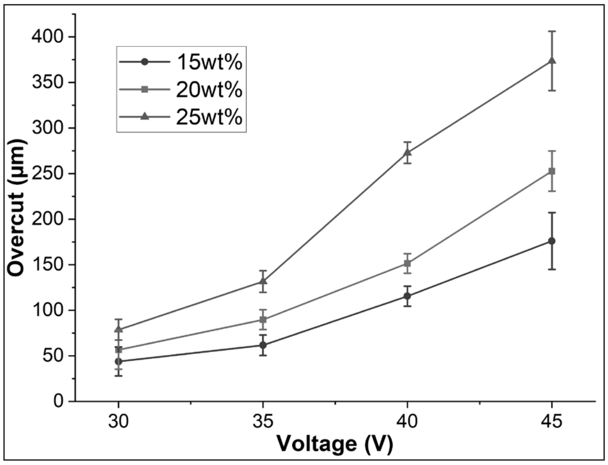

Fig. 4. Effects of voltage on overcut at different concentrations of electrolyte.

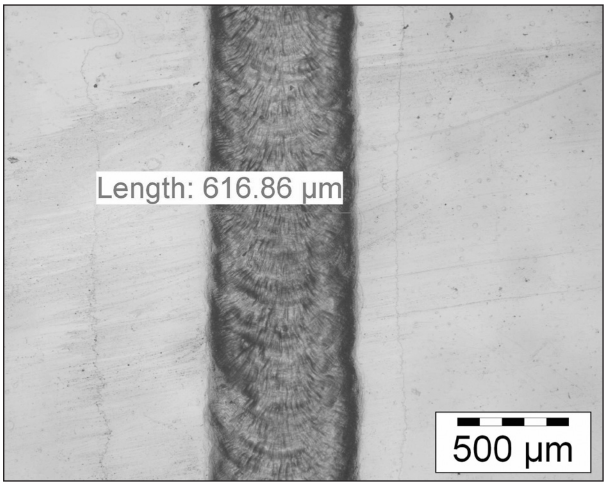

Fig. 5. Optical photograph of machined channel at 40V, 20wt% of concentration of electrolyte and 50µm/sec feed rate of tool.

Further, the new feeding technique involves the removal of machined materials due to gravity and led to increasing MRR than usual feeding technique.

3.2. Influence of concentration of electrolyte on MRR and overcut

The concentration of electrolyte has a vital role during milling operation with electrochemical discharge by increasing the electrical conductivity of the solution. Aqueous sodium hydroxide solution was used during the experimentation which provided sodium ion Na^+ as well as the hydroxyl ion $(OH)^-$ to the solution. With the increase of concentration of electrolyte, the number of sodium ions and hydroxyl ions in the solution also increases. A large number of ions ease the flow of current between two electrodes through the electrolyte thus increasing the electrical conductivity of the solution. With higher electrical conductivity the electrolysis process increase and the intensity of the spark discharge also increase. Fig.5 shows the optical image of machined channel at 40V, 20wt% of concentration of electrolyte and 50µm/sec feed rate of tool.

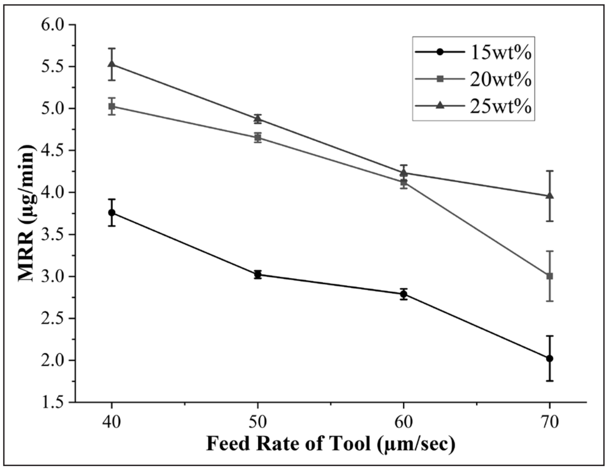

Fig. 6. Effects of the feed rate of tool on MRR at different concentrations of electrolyte.

The deviation in MRR and Overcut at a particular voltage was found to be lower at 15wt% and 20wt% of concentration of electrolyte and it is higher if the concentration is further increased. MRR and overcut of the machining were increased with the increase of concentration of electrolyte as shown in Fig.3 and Fig.4. The upward feeding technique allows to remove the machined materials from the machining zone due to gravity and the generated gas bubbles remains at the machining zone with the help of buoyancy of liquid which help in the formation of gas film and spark discharge.

3.3. Influence of feed rate of tool on MRR and overcut

The MRR and the overcut are significantly dependent on the feed rate of tool. If the feed rate of the tool increases then the tool-electrode gets less time to be in contact with the workpiece whereas it gets more time if the feed rate decreases. Spending more time at one point of the workpiece, the tool-electrode delivers more thermal energy in terms of spark discharge to remove materials from the workpiece. So, the decrease in the feed rate of tool increases the MRR as shown in Fig.6. At a lower feed rate of tool such as at 40µm/sec, the tool-electrode provides spark discharge at a particular point over and over again.

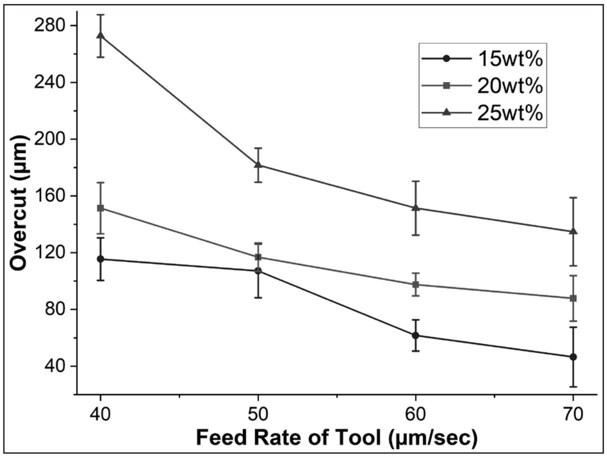

Fig. 7. Effects of the feed rate of tool on overcut at different concentrations of electrolyte.

Due to this action, MRR is higher at a lower feed rate of tool and gradually decreases to be lower at a higher feed rate of tool. More deviated value of MRR was obtained at 40µm/sec and 70µm/sec of tool feed rate due to large removal of material and uneven removal of material from the workpiece respectively. The effects of feed rate of tool on the overcut at different concentration of electrolytes are shown in Fig.7.

The overcut happens due to the unnecessary removal of materials from the workpiece if side sparking from the tool-electrode occurs. However with the help of new feeding technique the tool-electrode moves from the bottom of the liquid to the upward direction, which concentrates the bubbles at the machining area and reduces the chance of side sparking.

4. Conclusions

The ECD milling operation has been performed using horizontal tool-electrode and vertically upward feeding technique with the help of in-house developed machining set up. The parametric analysis of ECD milling process on MRR and overcut has been analysed. However, the following conclusions can be drawn from the present investigation:

- The newly developed horizontal tool-electrode and vertically upward feeding technique is very much appropriate in ECD milling. This technique not only helps to remove the machined material from the machining area but also increase the MRR and decrease the overcut.
- The MRR increases at higher voltage and higher concentration of electrolyte. It was found to be 6.297µg/min at 45V and 25wt% of concentration of electrolyte. Although the overcut at this range of parameter was very high.
- The overcut of machined channel was higher at higher voltage and it reaches up to 373.62µm at 45V and 25wt% due to intense discharge from side surface of tool-electrode. The MRR and overcut were also increased at lower feed rate of tool (40µm/sec).
- However, the value of MRR (5.025µg/min) with reasonably lower overcut (116.86µm) was observed at 40V of applied voltage, 20wt% of concentration of electrolyte and 50µm/sec of feed rate of tool.

This horizontal tool and vertically upward feeding technique cane utilized in making 3D features on advanced materials and machining can be improved with the addition of rotation and vibration of tool electrode.

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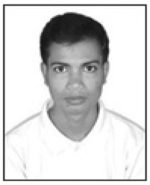

Sudip Santra is a Research Scholar of Production Engineering Department of Jadavpur University. He has completed his Bachelor of Technology in Mechanical Engineering Department of Kalyani Government Engineering College in 2015 and he has completed his Master of Technology from Maulana Abul Kalam Azad University of Technology (Formerly known as WBUT) in 2019. He has secured second position in M.Tech in the university. He also qualified GATE in 2016. Sudip Santra has 5 national and international research publications.

Dr. Biplab Ranjan Sarkar is a Professor and ex-Head of Production Engineering Department of Jadavpur University, Kolkata. He is actively engaged in teaching and research work in the area of advanced manufacturing technology. He has guided several M.E. and Ph.D (Engg.) theses on production engineering. He has published about 30 research papers in national and international conferences and journals and presented his research works in reputed conferences. He has worked as Co-PI on the sponsored project of AR & DB.
(E-mail: sarkarbiplab_s@rediffmail.com)

Dr. Biswanath Doloi is Professor and ex-Head of Production Engineering Department of Jadavpur University, Kolkata. He is actively engaged in teaching and research work in the area of advanced manufacturing technology. He has guided several M.E. and Ph.D (Engg.) theses on production engineering. He has published about 150 research papers in national and international conferences and journals and presented his research work in reputed conferences. He has completed a research project under the DST-SERC Fast Track Project for Young Scientists and also CSIR Extramural research project on laser micro-machining. He has authored a books published by Elsevier Inc, USA as well as edited two books published by Springer. He is a member of various professional bodies such as the Institution of Engineers (India) and Indian Society for Technical Education, New Delhi.
(E-mail: bdoloionline@rediffmail.com)

Dr. Bijoy Bhattacharyya, FINAE, is Professor and Head of the Production Engineering Department and Coordinator of Center of Advance Study Programme (Phase-II,III,IV) under University Grants Commission and Quality Improvement Programme under AICTE of Jadavpur University. His research areas include non-traditional machining, micro machining, advanced manufacturing systems, etc. He has published 176 research papers in National and International Journals and 315 research papers in National and International Conferences. He has published several book chapters and conference proceedings. He has authored two books published by Elsevier Inc, USA as well as edited five books published by Springer. Several Ph.D theses have been completed under his guidance. He has completed several research projects. He is recipient of various awards, e.g. Gold Medal and Certificate of Achievements for research papers and thesis as well as the Career Award of the UGC, New Delhi. (E-mail: bb13@rediffmail.com)