

Advancement of Electrochemical Discharge Machining Process—A Review



S. Santra , B. R. Sarkar , B. Doloi , and B. Bhattacharyya

Abstract Electrochemical discharge machining (ECDM) process, which is referred to as electrochemical spark machining, was known to the world due to the invention by Kurafuji and Suda in 1968. Research papers of the last few years have been reviewed to comprehend the process mechanism and its development up to the milling operation on electrically non-conductive materials. The basic mechanism and development of the ECDM process in terms of gas film stabilization, enhancement of MRR, and improvement of surface quality and dimensional accuracy have been discussed in this paper. The application of electrochemical discharge for milling operation and its development has also been incorporated in this paper. Further, the effects of the use of various electrolytes, tool electrode materials, tool electrode shape and application of vibration, magnetic field as well as the addition of various extra features to the basic process and the future scope of research have been discussed.

Keywords Electrochemical discharge machining · MRR · Microchannel · Micro-milling

1 Introduction

Machining is an essential manufacturing process toward the development of technology and its applications in various fields. Conventional machining ruled the field of manufacturing since stone from stone weapons to the development of CNC and artificial intelligence. Due to the presence of new and advanced materials, the development of machining technologies is also improving. In the age of non-traditional machining, there are a lot of processes, which have been used for machining hard, brittle, and difficult to machine materials like glass, ceramics, metal matrix, etc. Further, the development of a micro-electro-mechanical system (MEMS) pushed forward the micro-machining as well as non-traditional machining processes. Among

S. Santra (✉) · B. R. Sarkar · B. Doloi · B. Bhattacharyya
Production Engineering Department, Jadavpur University, Kolkata 700032, India
e-mail: sudip16santra@gmail.com

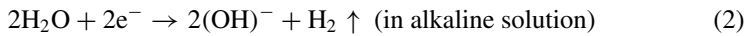
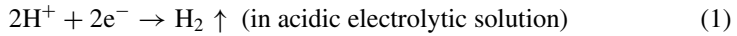
various kinds of non-traditional machining, there are some thermal, chemical, electrochemical, and mechanical machining processes depending on their material removal mechanisms. Every non-traditional machining process consists of advantages and limitations. The electrical discharge machining process can machine electrically conducting materials with a less hard tool than a workpiece. This process can be used to machine hard materials through the formation of recast layer, HAZ, and other thermal effects on the machined surface is the major drawbacks of this process. The electrically non-conducting materials cannot be machined by the EDM process [1]. Electrochemical machining processes are effective during machining of electrically conductive materials and surface finishing, deburring as well as micropattern can be developed through this process but only in electrically conductive materials [2]. The hybrid machining processes were introduced to overcome the limitations of the separate process. The addition of ultrasonic vibration, powder additives in the EDM process improved the surface finish and material removal rate in the EDM process [3]. Electrochemical discharge machining overcame the limitations present in ECM and EDM separately and was able to machine electrically non-conductive materials. ECDM process proved its effectiveness for machining alumina, borosilicate glass, etc. [4]. The process of electrochemical discharge was first discovered in Japan by Kurafuji and Suda though they did not use the term ECDM rather they proposed it as electrical discharge drilling [5]. After the 1990s lot of works were carried out to understand the process and its usability in the machining of electrically non-conductive materials like glass, ceramics, quartz, etc. [6]. Jain et al. used the term electrochemical spark machining (ECSM) in 1990 and developed a second-order model of responses using the CADEAG-1 software package [7]. In 1996, Singh et al. used cathode wire to machine partially conductive materials and found that material removal rate increased with the increase of supply voltage and electrolyte concentration within the range of machine conditions [8]. Research on the mechanism of spark generation was first carried out by Basak and Ghosh in 1996 [9, 10]. They developed a theoretical model and experimented to verify the model. Jain et al. in 1999 prepared a model for material removal rate by finite element modeling using 3D unsteady state heat conduction problem and observed that the computed MRR was higher than the experimental results [11].

2 Fundamentals of ECDM

Since the first invention of electrochemical discharge machining, researchers around the world have tried to understand the fundamental concept or behavior of the process. Till now it has not been fully understood phenomenon as the removal of materials, gas film formation, or like such things are used to happen during machining which is uncontrollable. It has been observed from the development of ECDM that material removal took place due to the combined effects of electrochemical reaction and electrical spark discharge [12]. During the investigation on non-conducting ceramics materials, Bhattacharyya et al. analyzed the electrochemical reaction that occurred

when voltage was applied between the two electrodes immersed into the electrolyte [13]. In ECDM, two electrodes are used which are immersed into the electrolyte and among them, one electrode is a cathode generally used as a tool and another electrode is an anode used as an auxiliary electrode. The size of the auxiliary electrode is much bigger than the tool electrode. The electrochemical reaction that happens in the system can be divided into two parts like reaction on cathode where the evolution of hydrogen gas occurs due to evaporation of electrolytes and reaction on anode where the evolution of oxygen gas occurs.

Reaction at cathode



Reaction at anode

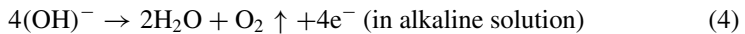
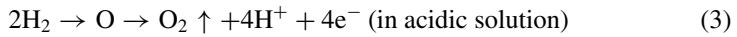


Figure 1 shows the schematic diagram of the experimental setup of the electrochemical discharge machining process.

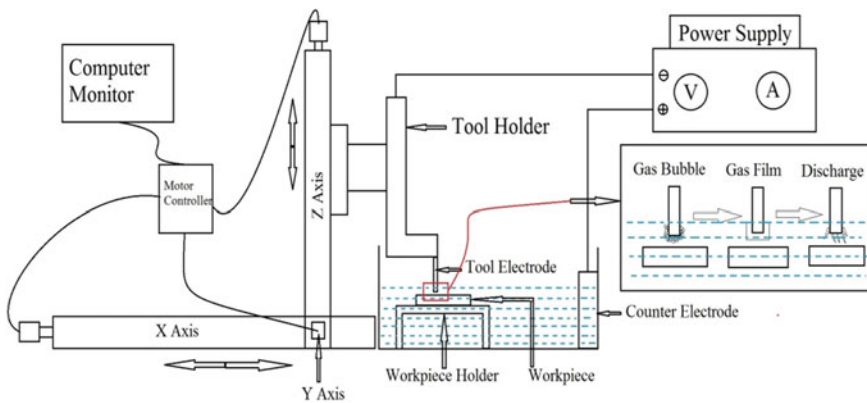


Fig. 1 Schematic diagram of the experimental setup of ECDM process

2.1 *Fishbone Diagram*

The size of the auxiliary electrode has to be around 100 times larger than the tool electrode. During the application of the voltage between two electrodes, the hydrogen gas bubbles generated by the evaporation of electrolytes accumulate around the tool electrode or cathode. These hydrogen gas bubbles are used to form gas film to cover the open area to the electrode with the increase of voltage. At a certain critical voltage, this gas film collapsed and discharge can be seen in the form of light emission. This discharge did not occur between the two electrodes rather it occurred between cathode and electrolyte [14]. Any electrically non-conductive materials placed in that discharge area are exposed to high thermal energy which melts and vaporized the materials from the workpiece. During the drilling of glass, Wüthrich et al. have increased material removal rate by twice than without vibration [15]. Some researchers have claimed that many phenomena can be monitored like local electrolyte temperature, presence, and absence of gas film by analyzing the current signal during the process [16]. Gas film thickness can be changed by improving the wettability of the tool in the electrolyte [17]. In direct polarity, material removal takes place by melting and vaporization, whereas in reverse polarity chemical reactions also happen with melting and vaporization. Although in reverse polarity overcut, tool wear and surface roughness are higher than direct polarity [18]. The thermal conductivity of the tool can also affect material removal. Mousa et al. [19] found that a tool with higher thermal conductivity can increase the material removal process due to its ability to vaporize more electrolytes in the discharge regime whether hydrodynamic regime material removal decreases due to higher viscosity of molten workpiece. Besides those, many research works have been done and till now development of this process is going on to understand the actual phenomenon that happens during electrochemical discharge and to stabilize it for commercial applications. Figure 2 shows the different effective factors which can influence the ECDM process, and Fig. 3 shows the application of ECDM in different fields.

3 **Advancement in ECDM**

3.1 *Control of Gas Bubbles and Gas Film*

Surface active agent or surfactant has the property to reduce the surface tension of the system. Surfactant SDS and CTAB with 25 wt% NaOH and 25 wt% KOH solution can decrease surface tension up to Critical Micelle Concentration (CMC). Due to decreased value of surface tension, the thin gas film produced as a large bubble is unable to be stuck with the tool electrode [20]. Lin et al. have added ethanol to the electrolyte which helped to reduce the angle between electrodes and as bubble, and magnetic field organized the charged particle due to Lorentz force and stabilized the generated flow around the electrode. Besides that minimum level of electrolyte,

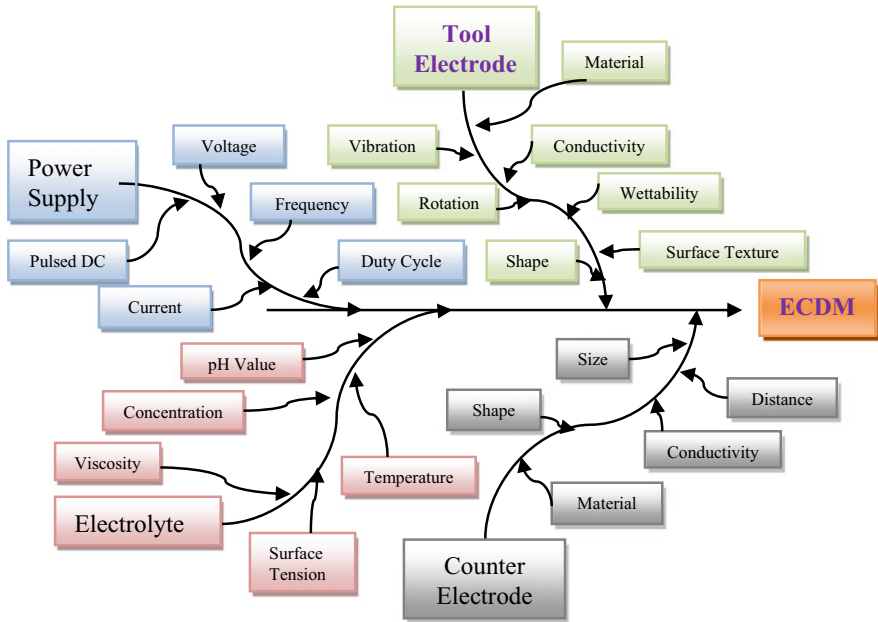


Fig. 2 Cause and effect of different factors in ECDCM

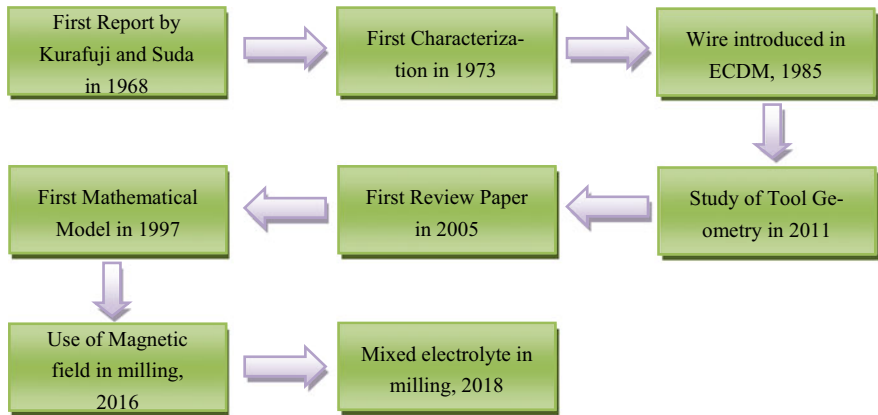


Fig. 3 Development of ECDCM

the minimum concentration of electrolyte and maximum possible distance between electrodes is suitable for stable gas film formation. Figure 4 shows the generated gas film under extreme and optimum conditions [21].

As the buoyancy force is a problem in a high level of electrolyte and more concentration of electrolyte accelerates the electrochemical process which enhanced the instability of gas film due to increased buoyant force. Arab et al. have documented

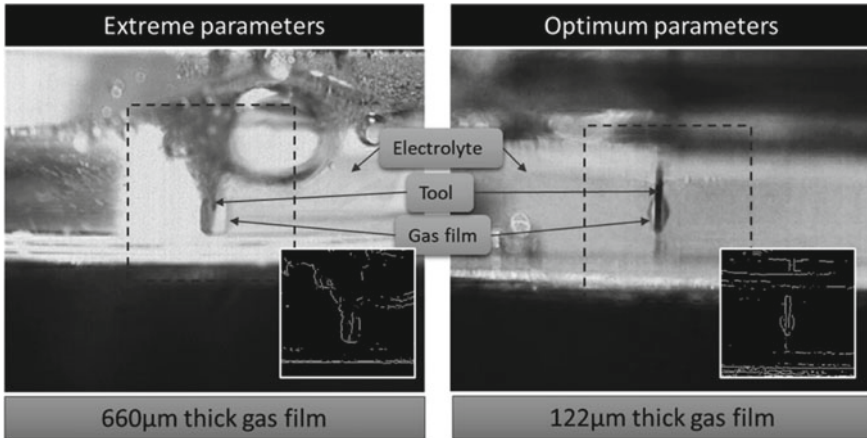


Fig. 4 Generated gas film in extreme and optimum condition [21]

that higher surface roughness tools are responsible for thicker gas bubbles and gas film thickness, whereas lower surface roughness tools produce thin gas film and lower HAZ [22]. Higher surface roughness tool can capture bigger gas bubbles due to the presence of dipper valley which produced the thicker gas film. Behroozfar et al. have reported that in 30 wt% NaOH solution with 35 V applied voltage and using 500 μm tungsten tool an average diameter of 260 μm of plasma channel can be obtained [12]. Assisted ultrasonic vibration of 10 μm amplitude to the tool electrode has reduced gas film thickness by 65%. Figure 5a shows the craters which were formed during electrochemical discharge machining, and Fig. 5b shows the nature of single discharge during ECDM [23, 24].

Gas film behavior is not only influenced by electrolyte, tool, or vibration in tool electrodes but also closely related to the gas bubble evaluation. The balance force acting on the gas bubble can be manipulated by applying extra Lorentz force which resulted in thinner gas film formation [25]. Appalanaidu et al. have controlled the gas film shape with the help of generated electrostatic force on hydrogen gas bubbles [26].

3.2 Enhancement of MRR

The application of ultrasonic vibration of 10 μm amplitude has resulted in 5.48 μg of material removal which is greater than without vibration. It has also been observed that a large amount of amplitude destroyed the effect of vibration [24]. Due to the reduction of gas film thickness through ultrasonic vibration, the discharge activities affect more than without vibration which leads to improvement of MRR [23]. Square

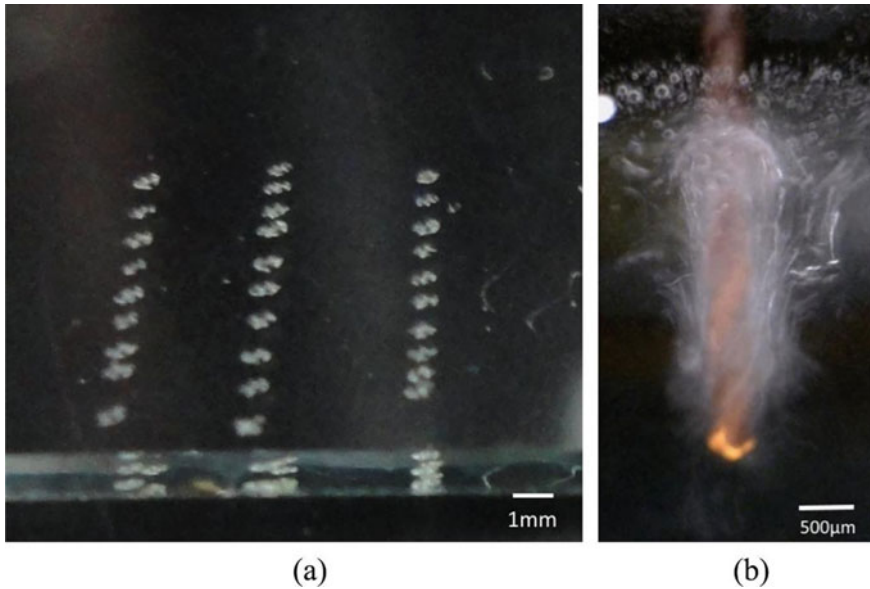


Fig. 5 Craters on a workpiece (a) and single discharge (b) [23]

waveform voltage to the actuator has increased MRR by 40% in the case of a cylindrical rod and 20% increase of MRR found when sinusoidal waveform applied [27]. Bellubbi et al. have observed that higher electrolyte concentration and machining time can increase MRR [28]. The electrolyte is a very important factor of ECDM because its properties like conductivity, viscosity, density, and temperature influence the gas film making process which leads to proper machining. A mixer of NaOH and KOH has provided more electrical conductivity than separate NaOH and KOH. The depth of the microchannel increased by 19% in the case of 25 wt% mixed electrolyte (NaOH + KOH) than 25 wt% KOH and increased by 31% than 25 wt% NaOH. Figure 6 shows the comparison of current signal among KOH, NaOH, and mixed electrolyte and visible that in case of mixed electrolyte of NaOH, KOH provides more current than other two [29].

By dispersing nanoparticles, Elhami et al. have improved hole depth improved by 21.1% for Al_2O_3 and 18.7% for Cu nanoparticles [30]. Application of electrolyte injection provides sufficient electrolyte even at a deeper hole to maintain the material removal mechanism. It also provides drag forces to detach smaller diameter bubbles from the cathode surface. It has been observed that the use of electrolyte injection increases the hole depth by 70% with a 1.7 mm diameter tool electrode [31]. Researchers also reported that continuous replenishment of vaporized electrolytes at the machining zone stabilized the discharging process. With this stable process, a noticeable amount of increase in hole depth was found [32]. The spherical head tool electrode made less contact with the workpiece and allows the electrolyte to flow in the machining zone which produce stable gas film and lead to an

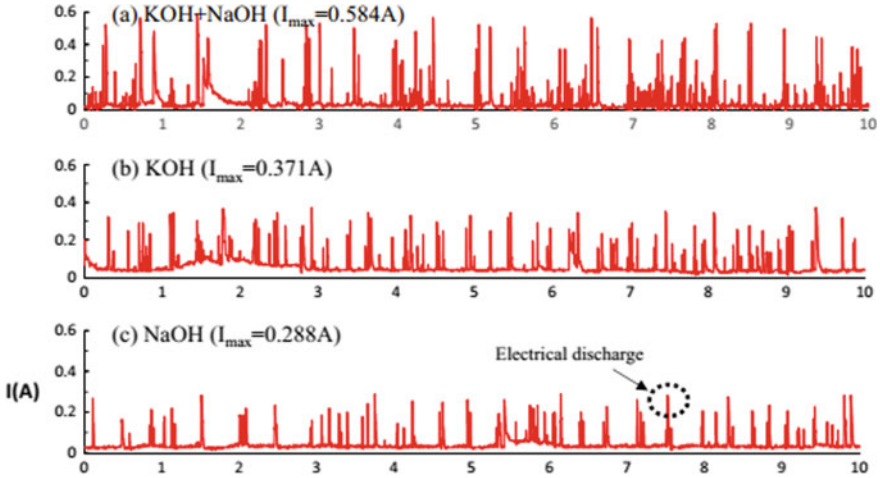


Fig. 6 Comparison of current signal between individual and mixed electrolytes [29]

increase in the machining depth by increasing MRR [33]. Ratan et al. have examined and observed that the presence of a magnetic field in the ECDM process generates Lorentz force onto the ion and helps them to move which creates magnetohydrodynamic convection. Due to MHD, convection electrolytes are used to flow through the small distance between electrodes and workpiece and more frequent sparking occurs which increases the MRR [34].

3.3 Improvement of Surface Quality and Dimensional Accuracy

The optimum tool-workpiece gap has a great impact on the surface quality and dimensional accuracy [35]. Experiments have shown that lower viscosity and higher ion mobility are the two major factors for a better quality of through-hole. In the case of KOH, the quality of the through-hole improved a lot [35]. Chenxiang et al. have found more tapering effect and bigger size hole diameter at higher conductivity solution of NaNO_3 [36]. To get more energy from electrochemical discharge, the concentration of electrolyte needs to be increased but at higher concentrations, the machined surface is damaged due to higher thermal conductivity. The mobility and thermal conductivities of potassium ions are greater than sodium ions, but the mixture of KOH and NaOH at 15 and 25% give higher thermal conductivity than separate KOH and NaOH which provide higher depth and better-machined quality [29]. A greater number of $(\text{OH})^-$ ion in the electrolyte have reduced the surface tension and produced the thinner gas film. The presence of $(\text{OH})^-$ ion also enhanced the chemical etching process and improves the quality of machined surfaces [37]. The mobility and

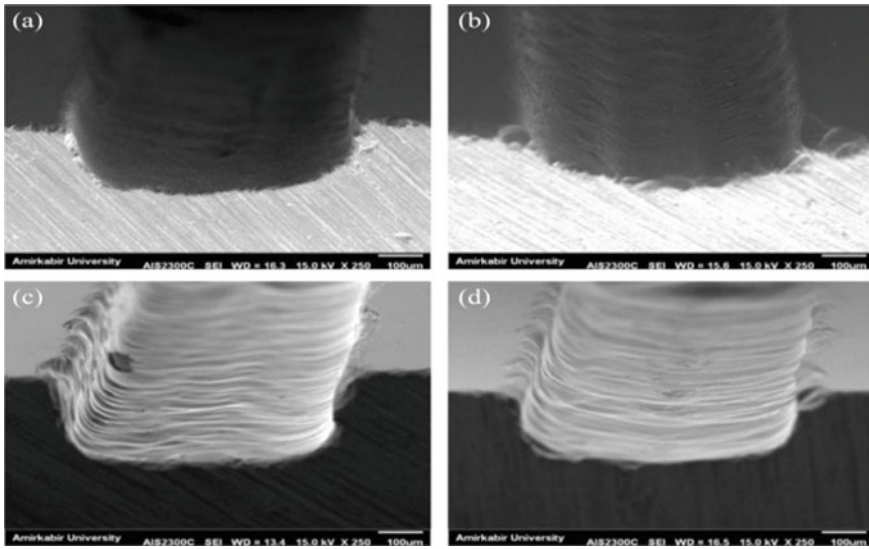


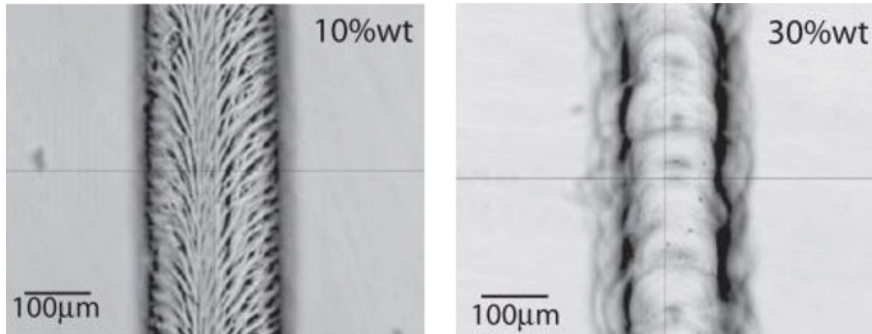
Fig. 7 Different machined surfaces at different electrolyte concentrations of 10–30% NaOH [38]

electrical conductivities of potassium ions are larger than sodium ions which helps the potassium ion to generate more power than sodium ion and consequently heat-affected zone is higher in KOH solution. Figure 7 shows different surface qualities at different electrolyte concentrations [38].

Lower tool electrode feed rate provides more interaction with the workpiece and time for the flow of electrolyte at the machining zone. It has been found by researchers that tool feed rates higher than 5 μm/s produced nonuniform electrochemical discharge. If the tool feed rate is lower than 5 μm/s, then uniform electrochemical discharge can be obtained which resulted in a smaller size of top hole and bottom hole diameter which was 300 μm and 70 μm, respectively at 3–4 μm/s feed rate [39].

3.4 MicroChannel and Milling with Electrochemical Discharge

The research work in the field of channeling and milling is very less compared to the drilling process. Some researchers experimented to find out the capability of ECDM in channeling and milling. Using surfactant in electrolytes, the surface quality of microchannels was improved due to the increase in the viscosity of electrolyte and decrease in the thermal conductivity [20]. Sabahi et al. have increased the depth of microchannel in case of a mixed electrolyte by 19% than KOH and 31% than NaOH solution, and the overcut values for NaOH, KOH, and mixed electrolyte



(a) Featherly like texture at 10wt% NaOH

(b) Spongy like texture at 30% NaOH

Fig. 8 Texture of machined surfaces at different electrolyte concentrations. **a** Featherly like texture at 10 wt% NaOH and **b** spongy-like texture at 30% NaOH [40]

are 655 μm , 638 μm , and 541 μm , respectively [29]. Electrolyte concentration has a prominent effect on the channel and milling process done by electrochemical discharge machining. Jana et al. observed that at 10wt% NaOH the surface of the machining zone became featherly like texture while by increasing the electrolyte concentration from 10 to 20 to 30 wt%; the featherly like texture became spongy-like texture. Figure 8a shows featherly like texture at 10 wt% NaOH, and Fig. 8b shows the spongy-like texture at 30 wt% NaOH solution [40].

Electrolyte temperature increases the energy of ions at the electrolyte surface which leads to more powerful discharge and a faster channeling process [41]. Higher electrolyte concentration increases the MRR by decreasing inter-electrode resistance but at higher electrolyte concentration, the sludge gets accumulated and side sparking increases [42]. The textured tool has resulted in an increase in MRR and depth of microchannel by 19.27% and 64.81%, respectively. In the case of microchannel, if the tool feed rate increased, then the channel depth decreased such as at lower feed rate channel depth was obtained 23 μm which was 11 μm in case of higher speed [40]. Low feed rate leads to longer interaction time between tool and workpiece which opens up the opportunity for chemical action and increased MRR [42, 43]. The large distance between tool and workpiece increased the kinetic energy as it travels more distance to collide with one another which deteriorates surface quality and reduces the area of groove [44, 45]. The use of the magnetic field in the micro-milling of glass by electrochemical discharge machining was very helpful as stated by Hajian et al. [46]. They published that at lower electrolyte concentration, the viscosity was lower which helped to remove the etched glass from the machining zone. The Lorentz force generated by the magnet controls the motion of gas bubbles at the inter-electrode area which improved the MRR. It has been observed that with the increase in applied voltage and electrolyte concentration, the tool feed rate was greatly increased [46, 47]. Another study has shown that by increasing electrolyte concentration, the channel depth can be increased but the surface quality will deteriorate in case of higher electrolyte concentration [47].

4 Significance

Machining a material with the help of non-conventional machining processes like electric discharge machining (EDM), electrochemical machining (ECM), abrasive water jet machining (AWJM), laser beam machining (LBM), etc., can be done but with certain limitations. Electrically non-conducting materials cannot be machined with ECM and EDM. Miniature product is difficult to fabricate with WAJM as overcut is a major problem here and skillful operators are required to operate the machine with the available setup. Transparent materials cannot be easily machined with the help of LBM. These disadvantages of the machining process enhance the demand for micro-electrochemical discharge machining process since conductive materials as well as electrically non-conductive, which are very difficult to machine can be easily machined by ECDM. No isolated chamber is required for the setup. No mask is needed and just as in traditional machining, the desired structure can be machined directly. Electrochemical discharge machining (ECDM) can machine materials irrespective of the electrical and mechanical properties with small thermal effect, i.e., formation of heat-affected zone of workpiece materials, and the area of machining zone can be varied from several millimeters to microns without large force as found in all common conventional machining processes.

5 Summary

After reviewing the research papers on the ECDM process, it has been observed that the process is very complex and uncertain. Lots of phenomena happen during the machining process, and most of the researchers agreed that electrochemical and electrical discharge machining process both occurs in the ECDM process. In this machining process, if a high-temperature etching process happens during machining, then the quality of machining or the machined surface became smooth surface. During the milling tool-workpiece distance and tool-workpiece interaction, time plays a vital role in the smooth milling surface. The addition of surfactant to the electrolyte reduces the surface tension which provides thinner gas film besides that adding vibration to the tool electrode also provides thinner gas film. Different types of tool electrodes, electrolytes, and the addition of magnetic field, vibration may improve the total machining efficiency. From the above discussions, the following conclusions can be made.

- The use of surfactant reduces the surface tension of the medium and the addition of vibration to the tool electrode leads to thinner gas film, and thinner gas film can produce a smooth surface. Using surfactant in electrolyte, the surface quality of microchannels was improved due to the increase in the viscosity of electrolyte and decrease in the thermal conductivity.

- The evaluation of gas bubbles is also an important factor that can be triggered by using a magnetic field to the system where the Lorentz force helps to organize the generated gas bubbles.
- Higher surface roughness tools produce bigger bubbles due to the presence of peak and valley, and the minimum electrolyte concentration and maximum inter-electrode distance may produce the suitable gas film.
- A mixed alkaline solution can produce a better microchannel in glass materials.
- Lower tool electrode feeding provides more time for tool-workpiece interaction which leads to high-temperature etching and smooth machined surface.

6 Future Scope

The complex phenomenon of ECDM is not still well understood. Drilling of non-conductive materials like glass, ceramics, quartz, etc., has been carried out by applying different techniques. Still lot of research is required to make the process commercialized. Very few research papers are available regarding channeling or milling. The process is highly dependent on various factors like workpiece materials, tool electrodes, power supply, electrolytes properties, tool feed rate, etc. So, many factors need to optimize properly to get smooth and accurate machining.

Control of gas film:

- Analysis of electrolyte properties like concentration, viscosity, surface tension by addition of abrasives, mixed electrolyte, surfactant, etc.
- Application of vibration and use of a lower surface textured tool to control the size of the gas bubble.
- Application of magnetic field to organize the gas bubble.

Enhancement of MRR:

- The continuous flow of electrolytes or application of proper flushing techniques.
- Use of appropriate tool electrodes so that availability of electrolyte can make at the machining zone.
- Analysis of voltage application needed at the different conditions to increase MRR without compromising the machining quality.

Improvement of machined quality:

- Generation of the lower gas film reduced the HAZ and tapering effect and the gas film can be reduced by different combinations of effective parameters.

Continuous maintaining of machining gap and tool rotation can also provide a smooth machined surface.

References

1. Ho KH, Newman ST (2003) State of the art electrical discharge machining (EDM). *Int J Mach Tools Manuf* 43(13):1287–1300
2. Bhattacharyya B, Munda J, Malapati M (2004) Advancement in electrochemical micro-machining. *Int J Mach Tools Manuf* 44(15):1577–1589
3. Abbas NM, Solomon DG, Bahari MF (2007) A review on current research trends in electrical discharge machining (EDM). *Int J Mach Tools Manuf* 47(7–8):1214–1228
4. Jain VK, Choudhury SK, Ramesh KM (2002) On the machining of alumina and glass. *Int J Mach Tools Manuf* 42(11):1269–1276
5. Kurafuji H, Suda K (1968) Electrical discharge drilling of glass. *Ann CIRP* 16:415–419
6. Gouda M, Sharma AK, Jawalkarb C (2016) A review on material removal mechanism in electrochemical discharge machining (ECDM) and possibilities to enhance the material removal rate. *Precis Eng* 45:1–17
7. Jain VK, Tandon S, Kumar P (1990) Experimental investigations into electrochemical spark machining of composites. *J Eng Ind* 112(2):194–197
8. Singh YP, Jain VK, Kumar P, Agrawal DC (1996) Machining piezoelectric (PZT) ceramics using an electrochemical spark machining (ECSM) process. *J Mater Process Technol* 58(1):24–31
9. Basak I, Ghosh A (1996) Mechanism of spark generation during electrochemical discharge machining a theoretical model and experimental verification. *J Mater Process Technol* 62(1–3):46–53
10. Basak I, Ghosh A (1997) Mechanism of material removal in electrochemical discharge machining a theoretical model and experimental verification. *J Mater Process Technol* 71(3):350–359
11. Jain VK, Dixit PM, Pandey PM (1999) On the analysis of the electrochemical spark machining process. *Int J Mach Tools Manuf* 39(1):165–186
12. Behroozfar A, Razfar MR (2016) Experimental and numerical study of material removal in electrochemical discharge machining (ECDM). *Mater Manuf Process* 31(4):495–503
13. Bhattacharyya B, Doloi BN, Sorkhel SK (1999) Experimental investigations into electrochemical discharge machining (ECDM) of non-conductive ceramic materials. *J Mater Process Technol* 95:145–154
14. Wüthrich R, Fascio V (2005) Machining of non-conducting materials using electrochemical discharge phenomenon—an overview. *Int J Mach Tools Manuf* 45(9):1095–1108
15. Wüthrich R, Despont B, Maillard P, Bleuler H (2006) Improving the material removal rate in spark-assisted chemical engraving (SACE) gravity-feed micro-hole drilling by tool vibration. *J Micromech Micro Eng* 16(11):N28–N31
16. Wüthrich R, Spaelter U, Bleuler H (2006) The current signal in spark-assisted chemical engraving (SACE) what does it tell us. *J Micromech Micro Eng* 16(4):779–785
17. Wüthrich R, Hof LA (2006) The gas film in spark assisted chemical engraving (SACE)—A key element for micro-machining applications. *Int J Mach Tools Manuf* 46(7–8):828–835
18. Jain VK, Adhikary S (2008) On the mechanism of material removal in electrochemical spark machining of quartz under different polarity conditions. *J Mater Process Technol* 200(1–3):460–470
19. Mousa M, Allagui A, Ng HD, Wüthrich R (2009) The effect of thermal conductivity of the tool electrode in spark-assisted chemical engraving gravity-feed micro-drilling. *J Micromech Micro Eng* 19(1):1–7
20. Sabahi N, Razfar MR, Hajian M (2017) Experimental investigation of surfactant-mixed electrolyte into electrochemical discharge machining (ECDM) process. *J Mater Process Technol* 250:190–202
21. Kolhekar KR, Sundaram M (2018) Study of gas film characterization and its effect in electrochemical discharge machining. *Precis Eng* 53:203–211
22. Arab J, Kannoja HK, Dixit P (2019) Effect of tool electrode roughness on the geometric characteristics of through-holes formed by ECDM. *Precis Eng* 60:437–447

23. Elhami S, Razfar MR (2017) Analytical and experimental study on the integration of ultrasonically vibrated tool into the micro electro-chemical discharge drilling. *Precis Eng* 47:424–433
24. Elhami S, Razfar MR (2018) Effect of ultrasonic vibration on the single discharge of electrochemical discharge machining. *Mater Manuf Process* 33(4):444–451
25. Xu Y, Chen J, Jiang B, Liu Y, Ni J (2018) Experimental investigation of magnetohydrodynamic effect in electrochemical discharge machining. *Int J Mech Sci* 142–143:86–96
26. Appalanaidu B, Dvivedi A (2020) On controlling of gas film shape in electrochemical discharge machining process for fabrication of elliptical holes. *Mater Manuf Processes* 36(5):558–571
27. Razfar MR, Behroozfar A, Ni J (2014) Study of the effects of tool longitudinal oscillation on the machining speed of electrochemical discharge drilling of glass. *Precis Eng* 38:885–892
28. Bellubbi S, Naik R, Sathisha N (2021) An experimental study of process parameters on material removal rate in ECDM process. *Mater Today: Proc* 35(3):298–302
29. Sabahi N, Razfar MR (2018) Investigating the effect of mixed alkaline electrolyte (NaOH + KOH) on the improvement of machining efficiency in 2D electrochemical discharge machining (ECDM). *Int J Adv Manuf Technol* 95:643–657
30. Elhami S, Razfar MR (2020) Application of nano electrolyte in the electrochemical discharge machining process. *Precis Eng* 64:34–44
31. Mehrabi F, Farahnakian M, Elhami S, Razfar MR (2018) Application of electrolyte injection to the electro-chemical discharge machining (ECDM) on the optical glass. *J Mater Process Tech* 255:665–672
32. Arya RK, Dvivedi A (2019) Investigations on quantification and replenishment of vaporized electrolyte during deep micro-holes drilling using pressurized flow-ECDM process. *J Mater Process Tech* 266:217–229
33. Yang CK, Wu KL, Hung JC, Lee SM, Lin JC, Yan BH (2011) Enhancement of ECDM efficiency and accuracy by spherical tool electrode. *Int J Mach Tools Manuf* 51(6):528–535
34. Ratan N, Mulik RS (2017) Improvement in material removal rate (MRR) using magnetic field in TW-ECSM process. *Mater Manuf Process* 32(1):101–107
35. Arab J, Mishra DK, Dixit P (2021) Measurement and analysis of the geometric characteristics of microholes and tool wear for varying tool-workpiece gaps in electrochemical discharge drilling. *Mesurement* 168:108463
36. Arab J, Mishra DK, Kannoja HK, Adhale P, Dixit P (2019) Fabrication of multiple through-holes in non-conductive materials by electrochemical discharge machining for RF MEMS packaging. *J Mater Process Tech* 271:542–553
37. Zhang C, Xu Z, Hang Y, Xing J (2019) Effect of solution conductivity on tool electrode wear in electrochemical discharge drilling of nickel-based alloy. *Int J Adv Manuf Technol* 103(1–4):743–756
38. Yang CP, Wu KL, Mai CC, Wang AC, Yang CK, Hsu YS, Yan BH (2010) Study of gas film quality in electrochemical discharge machining. *Int J Mach Tools Manuf* 50(8):689–697
39. Sabahi N, Hajian M, Razfar MR (2018) Experimental study on the heat-affected zone of glass substrate machined by electrochemical discharge machining (ECDM) process. *Int J Adv Manuf Technol* 97:1557–1564
40. Arab J, Dixit P (2020) Influence of tool electrode feed rate in the electrochemical discharge drilling of a glass substrate. *Mater Manuf Process* 35(15):1749–1760
41. AbouZiki JD, Didar TF, Wuthrich R (2012) Micro-texturing channel surfaces on glass with spark assisted chemical engraving. *Int J Mach Tools Manuf* 57:66–72
42. Torabi A, Razfar MR (2021) The capability of ECDM in creating effective microchannel on the PDMS. *Precis Eng* 68:10–19
43. Yang CK, Cheng CP, Mai CC, Wang AC, Hung JC, Yan BH (2010) Effect of surface roughness of tool electrode materials in ECDM performance. *Int J Mach Tools Manuf* 50(12):1088–1096
44. Singh T, Dvivedi A (2018) On performance evaluation of textured tools during micro-channeling with ECDM. *J Manuf Process* 32:699–713
45. Changjian L, An G, Meng L, shengyi Y (2012) The micro-milling machining of pyrex glass using the electrochemical discharge machining process. *Adv Mater Res* 403–408:738–742

46. Hajian M, Razfar MR, Movahed S (2016) An experimental study on the effect of magnetic field orientations and electrolyte concentrations on ECEDM milling performance of glass. *Precis Eng* 45:322–331
47. Lin MY, Tsai TH, Hourng LW, Wang WK (2019) The effects of magnetic field and ethanol addition on the electrochemical discharge machining. *Int J Adv Manuf Technol* 105(5–6):2461–2467
48. Hajian M, Razfar MR, Movahed S, Etefagh AH (2018) Experimental and numerical investigations of machining depth for glass material in electrochemical discharge milling. *Precis Eng* 51:521–528