A Theoretical analysis on Electro Chemical Discharge Machining using Taguchi Method

Abhishek Charak\textsuperscript{1}, C.S Jawalkar\textsuperscript{2}\textsuperscript{*}
Department of Production and Industrial Engineering Department, Punjab Engineering College (Deemed to be University), Chandigarh 160012,
Email: c.sjawalkar@gmail.com

Abstract

The Electrochemical discharge machining (ECDM) is a growing machining process that develops from the processes like electrochemical machining (ECM) and electric discharge machining (EDM), used in micro machining of usually non-conductive materials such as quartz, glass, composites and ceramics. In recently time the need of non-conductive materials has been grown rapidly in the field of aerospace, medical, electrical and optical applications. Such as these applications implicate machining with higher reliability and higher accuracy, ECDM process has lavish scope in this area. Some further methods also that can machine non-conductive materials but they have certain limitations. In the current time ECDM is an emerging process, continuously researchers are trying to improve and amend it as a better way for non-conducting materials. Currently this paper carried out a study on continuous improvements in ECDM in machining of glass in the ECDM, has been show their effect on material removal (MR). A Taguchi analysis on machining of borosilicate glass has also been obtained, wherein it is illustrated that increase in feed rate and electrolyte concentration increases the MR.

Keywords: Electric Discharge Machining, Electro Chemical Machining, Electro Chemical Discharge Machining, Taguchi, ANOVA.

1. Introduction

Electrochemical Discharge Machining is an emerging non-traditional hybrid machining process that has attracted much research interest. It is a combination of two well-known processes, EDM and ECM. ECDM was first developed and presented by Kura Fuji in 1968 [1] for the machining of glass. Numerous modifications and hybridisations have been done in this process and different researchers have given other names such as Electrochemical Arc Machining and Electrochemical spark machining by Wuthrich et al.,[2] etc. In recent years non-conductive materials have increased demand in engineering applications because of their excellent properties such as high chemical resistance, high creep and high heat resistance etc., however machining with high accuracy and high reliability is a challenge. As ECDM is not restricted to machine only conductive materials as compared to other non-traditional processes, it has great potential in micromachining of hard nonconductive materials economically like soda lime glass, silicon wafers, ceramics which possess great challenge to their machining [3]. In ECDM various tools are employed like copper tungsten, high speed steel, stainless steel etc. for the machining process. Similarly for etching effect during the process various electrolytes are used like NaOH, KOH and NaNO\textsubscript{3} etc. which provides better results [4].

The work part to be machined in ECDM. As it is immersed in a base electrolyte solution like NaCl, NaOH or KOH. Two electrodes are immersed into the electrolyte. The tool (cathode) electrode is immersed few millimetres in the electrolyte and the auxiliary electrode (anode) is set aside from the tool electrode(cathode). As D.C voltage is applied within two electrodes, at that time formation of hydrogen gas bubbles start at the tool part electrode (cathode) and the formation of oxygen bubbles at the auxiliary part electrode (anode)[5]. For instance the terminal voltage is increased and the current density also increases, as a result bubbles increases and grow at a faster rate which arrange a layer of bubbles around the electrodes. If voltage is rises above the critical voltage they coalescence into a gas film around the tool electrode. This gas film acts a dielectric and creates sufficient resistance to generate high potential difference between the two electrodes. Potential difference is sufficiently high sparking phenomena is observed in the film where critical discharge happens between the tool electrode and the surrounding electrolyte [6]. If the work part is sited in the vicinity of the sparking
zone, machining takes place in the form of melting and vaporization of the material due to heat generated. Thus, instantaneous chemical etching also subsidises to machining operation. ECDM process is an intricate process which depend upon various different process parameters such as electrolyte concentration, applied voltage, speed and feed rate, inter electrode gap etc. and the process are calculated as material removal rate (MRR), tool wear rate (TWR) and surface roughness. Though, it is still unclear that which factors effect the machining performance most and how these parameters can be optimized [7]. The optimum selection of process parameter plays an important role in order to improve the quality of product and to improve the performance of the process. Therefore proper optimisation of parameters is very essential in order to understand the interaction between process parameters and response parameters of ECDM process. The fig. 1 (Charak, A. and Jawalkar) [8] shows a schematic sketch of ECDM process and shows a typical rough machined cut on a glass specimen.

![Fig.1 Schematically of ECDM Process](image)

### 2.0 Process Parameters For ECDM

The material removal in the ECDM is governed by the erosion of material due to electrical discharge and chemical etching. The main factors that affect the rate of machining are electrolyte concentration, voltage, inter-electrode gap etc., further the geometry, condition and accuracy of the machined surfaces depend upon them.

#### 2.1 Electrolyte

The effect of electrolyte on machining is hard to understand and cannot be described completely as a function of concentration and temperature. As discussed above, the machining process is partially a chemical one and therefore the nature of the electrolyte influences strongly the machining behaviour. The many kinds of electrolytes NaOH, KOH, NaNO3 NaF, NaCl, HCl, H2SO4 can be used. Among them NaOH seems to have the most interesting properties compared to other electrolytes as it improves MRR [9]. In this research also NaOH is used; however, KOH is also widely used due to its certain advantages.

#### 2.2 Voltage

Generally DC voltage is applied between the tool electrode and auxiliary electrode. As machining voltage is increased, the machining rate is increased. The machining rate reaches its maximum value at a particular voltage and then decreases. It is observed that a power supply which maintains a constant voltage throughout the machining process is the most effective for electrochemical discharge machining [10].
2.3 Inter electrode gap
When the gap is between the cathode (tool electrode) and the anode (auxiliary electrode). This gap is taken in order of few cm. Inter electrode gap affects machining rate and it was observed that as it increases, machining rate decreases.

2.4 Abrasives
When abrasive is mixed to electrolyte it is observed that there is improvement in the surface roughness by refining the micro-cracks and HAZ zone developed by heat erosion during discharge. C.T. Yang et al., [11] deduce that on adding abrasive materials to the electrolyte solution the value of critical voltage increase and reduction in slit expansion. Min Seop Han et al., [12] explain that on increasing concentration of abrasive the MRR increase and surface roughness decreases. Y S Liao et al., [13] research show that use of 0.5-1.0%wt graphite powder is preferred because it helps in reducing the micro cracks formed on glass.

2.5 Machining of glass
Research has been conducted on ECDM have tried to improve the capacity of the process by employing extra inductance in the ECDM circuit and noticed that there is a significant increase in MRR[14]. The study of the hardness and density variation in ECDM process while machining soda lime glass and explain that it occurs due sudden and quick quenching of the workpiece during machining. Liu et al., [15] have worked on improving the micro-structuring of soda lime glass by using a load cell which helps to reduce the required voltage by maintaining a constant gap between tool and workpiece. They noticed that pulsed voltage improves surface finish and smallest machining gap can be achieved by using KOH electrolyte. Some researchers tries to find different aspects that can improve this process further like Lijo Paul et al., [16] have identified the effect of power source by employing ANFIS and show that MRR can be increased by using pulsed DC as compared to normal DC while machining borosilicate glass. Jawalkar et al., [17] reviewed on different materials machining conditions in ECDM and reported that voltage is the most influential parameter in both MRR and TWR. Goud et al., [18] go through the study of various parameters and apart from the voltage and concentration parameters and showing that lower electrolyte concentration can affect the surface integrity of the workpiece which results in surface wrinkles around the periphery of drilled hole because at lower concentration chemical etching is more dominant as compared to thermal energy.

2.6 Machining of ceramics and composites
Ceramics finds its applications in various fields like. Ceramics such as aluminium oxide, zirconium oxides and silicon nitrides are widely used in bearings, computer parts, artificial joints, cutting tools, electrical components, and much more but it is difficult to machine it with economically and accurately. Jain et al., [19] proposed a new theory of increased MRR by using reverse polarity in ECDM but has some limitations of increased overcut, tool wear and surface roughness. Kulkarni et al., [20] discussed about the discharge mechanism of electrochemical discharge machining of particulate reinforced matrix and predicted that the critical voltage of breakdown occurs between 26.2-34.2 V. Experimentation by Lao et al.,[21] have shown that drilling quality of ECDM while machining quartz can be improved by adding surfactant sodium dodecyl sulphate(SDS) in electrolyte which increases the current density by enhancing bubble formation at the electrode, thus increases the engraving speed. Dhanvijay et al., [22] have studied the micromachining of ceramics using stagnant and flow electrolyte method and reported that electrolyte flow has significant increase in MRR as compared to stagnant flow. Lijo et al., [23] have shown by grey relational analysis that MRR depends on applied voltage and in order to reduce DOC and HAZ applied voltage should be around 45V and electrolyte concentration should be around 30wt% during machining. It also encounters with the uncontrolled chemical reactions as a result of mixed electrolytes which result in irregular micro features. Jain et al., considered voltage and table feed as a variable in machining of quartz and stated that MRR increases with increase in voltage because of increase in energy content of spark, on the other hand lower table feed results in more concentrated energy at a particular location and hence more MRR. Bhondwe
et al., [24] have predicted the MRR in ECSM of glass and ceramics using FEM modelling and conclude that in soda lime glass MRR goes on increasing significantly for electrolyte concentration between 10 to 20% and beyond this concentration has no effect to increase the MRR whereas in case of alumina it increases with increase in concentration of electrolyte. They also reported that with increase in duty factor MRR increases in both soda lime glass and alumina. Kuo et al., [25] have provided the results on better machining status with spherical tool electrode as compared to cylindrical tool electrode while machining quartz. They explained it on the basis of less contact area between tool and workpiece and more uniform formation of gas film around the spherical tool. Experimentation revealed by Yang et al., [26] have shown that surface roughness of the tool electrode has significant effect on wettability of tool which in turn responsible for the stability of gas film around the tool. Bhattacharya et al., [27] have carried out their study on influencing parameter like electrolyte concentration and applied voltage and proposed optimum voltage range between 70-90 V, beyond which, cracks can result on the surface. The Fig.2 presents research possibilities in the area of ECDM.

Figure 2. Research Possibilities in different areas of ECDM possible outcomes (Adapted from Goud et al., 2016)

3.0 Experimental procedure

The tool is prepared to the required geometry on a precision lathe, the machining chamber is cleaned with distilled water. The electrolyte and surfactant solution of the required concentration is prepared. The work piece is then placed and clamped in the machining chamber. Set the feed of the work piece by adjusting motor speed using controller. Tool was placed at a gap of 0.12mm from the work piece. The voltage is applied using DC power source and the experimental readings are noted. The experiments were performed for fixed machining time of 10 minutes. The following process parameters as mentioned in Table 1 are set in the experimentation process. The reduction of speed of the PWM DC motor was done through speed controller from 0 to 5 rpm by using knob regulator provided on it.

Table 1: Various parameters and their values:

| Constant parameters:          |                                |
|-------------------------------|--------------------------------|
| Tool material                 | Stainless steel                |
| Working cycle                 | 10 min                         |
| Work piece material           | Fused transparent quartz       |
Auxiliary electrode material: Mild steel
Initial electrode distance: 50-100 mm
Current settings: As per transformer rating
Rotational speed of the motor: 5 rpm
Linear velocity of the machining container: 7.5 mm/min

Variable parameters:
- Applied voltage: 65-85 V
- Electrolyte concentration: 15-25%
- Feed rate: 0.4-1.2 rpm
- Additives: Abrasive powders

3.1 Use of Optimization Technique

The Taguchi L9 orthogonal array is used to design the experiments at three levels as given in Table 2.

Table 2: Taguchi’s L9 Orthogonal array and assigned parameters

| Levels | Applied voltage (V) | Electrolyte conc. (%) by wt. | Abrasive (Type) | Feed rate (rpm) |
|--------|---------------------|------------------------------|-----------------|-----------------|
| 1      | 65                  | 15                           | No abrasive     | 0.4             |
| 2      | 75                  | 20                           | SiC             | 0.8             |
| 3      | 85                  | 25                           | Graphite        | 1.2             |

We are using four factors at three levels, so the table consist of the standard L9 orthogonal array for any combination of four factors as shown in Table 3.

Table 3: L9 orthogonal array for input process parameters and their levels

| Experiment | Applied voltage (V) | Electrolyte conc. (%) by wt. | Abrasive powder (%/wt.) | Feed rate (rpm) |
|------------|---------------------|------------------------------|--------------------------|-----------------|
| 1          | 65                  | 15                           | No abrasive (0)           | 0.4             |
| 2          | 65                  | 20                           | Graphite (2)              | 0.8             |
| 3          | 65                  | 25                           | Silica (2)                | 1.2             |
| 4          | 75                  | 15                           | Graphite (2)              | 1.2             |
| 5          | 75                  | 20                           | Silica (2)                | 0.4             |
| 6          | 75                  | 25                           | No abrasive (0)           | 0.8             |
| 7          | 85                  | 15                           | Silica (2)                | 0.8             |
| 8          | 85                  | 20                           | No abrasive (0)           | 1.2             |
| 9          | 85                  | 25                           | Graphite (2)              | 0.4             |

4.0 Results and their Discussions

The obtained experimental results at various experimental conditions have been illustrated in Table 4. In all three readings were taken and its average was considered for further analysis.

Table 4: Experimental L9 orthogonal array for input process parameters

| S. No. | Voltage (V) | Elect. Conc. (%/wt.) | Additives (2%/wt.) | Feed rate (rpm) | MR (mg) |
|--------|-------------|-----------------------|--------------------|-----------------|---------|
|        |             |                       |                    | 1               | 2       | 3       | Average |
| 1      | 65          | 15                    | No                 | 0.4             | 0.574   | 0.561   | 0.569   | 0.568   |
| 2      | 65          | 20                    | Graphite           | 0.8             | 0.867   | 0.858   | 0.871   | 0.865   |
| 3      | 65          | 25                    | Silica             | 1.2             | 0.302   | 0.325   | 0.317   | 0.315   |
| 4      | 75          | 15                    | Graphite           | 1.2             | 0.632   | 0.598   | 0.614   | 0.614   |
| 5      | 75          | 20                    | Silica             | 0.4             | 0.923   | 0.938   | 0.929   | 0.93    |
| 6      | 75          | 25                    | No                 | 0.8             | 0.787   | 0.791   | 0.797   | 0.792   |
| 7      | 85          | 15                    | Silica             | 0.8             | 0.987   | 1.058   | 0.993   | 1.013   |
| 8      | 85          | 20                    | No                 | 1.2             | 0.453   | 0.465   | 0.448   | 0.4553  |
| 9      | 85          | 25                    | Graphite           | 0.4             | 1.327   | 1.318   | 1.321   | 1.322   |
4.1 Analysis using ANOVA: In the Taguchi technique, the least difference and the optimal parameters are attained by means of the S/N ratio. The delta value represents the difference between the highest and lowest average assessment of S/N ratio for each factor. The analysis was done using MINITAB 17 software. It is illustrated in Table 5. As it was noticeable from the F-values column, the work piece feed rate was the most influencing factor in machining of fused transparent quartz through ECDM process. The applied voltage was the second most influencing parameters followed by abrasive powders. The electrolyte concentration was the least influencing parameters in this work.

| Source        | SS      | DOF | Variance (V) | F-value    | P-value  |
|---------------|---------|-----|--------------|------------|----------|
| Applied Vol.  | 26.17766| 1   | 26.17766     | 1.459098   | 22.13441 |
| Elect. Conc.  | 0.150345| 1   | 0.150345     | 0.00838    | 0.127124 |
| Abrasive      | 20.17482| 1   | 20.17482     | 1.12451    | 17.05874 |
| Feed rate     | 71.76396| 1   | 71.76396     | 4          | 60.67972 |
| Error         | 71.76396| 4   | 17.94099     | 1          | 0        |
| Total Sum     | 208.1684| 8   |              |            | 100      |

4.2 Effect of Applied Voltage and Electrolyte Concentration on MR

The figure 3 shows the relationship between applied voltage and material removal. As the value of the voltage increases the material removal rate also increases. Due increases in the voltage the bubble film can be easily broken and strong amount spark is produced which results in easier melting of the material. As the voltage increases, high amount of thermal energy produced which results in increases in material removal. In electrolyte concentration the figure shows relationship between electrolyte concentration and material removal rate. From the graph it was observed that as there was increase in electrolyte concentration the material removal rate increases mainly due to the increase in formation of ions which leads to high erosion effect and thermal discharging.

![Figure 3(a) Effect on applied voltage on MR(b) Effect on electrolyte conc. on MR](image)

4.3 Effect of Abrasive Powder and Feed Rate on MR

The figure 4 illustrates the effect of use of abrasive powder on the material removal. Material removal rate was more in case of addition of abrasive powders as compare to the condition when no abrasive was used. Also graphite had more material removal rate as compare to silica powder. With the addition of graphite powder the intensity of the spark increase which lead to high thermal energy and the material removal increases. Figure shows the effect of feed rate on the material removal rate of the transparent quartz work piece. As the feed rate of the work piece increases the
material removal rate decreases. For very time the intensity of spark generated located at a particular position.

![Main Effects Plot for MR](image1.png)

**Figure 4 (a) Effect of abrasive powder on MR (b) Effect of feed rate on MR**

### 4.4 Main Effect Plot for Means of MRR and S/N Ratios of MR

As evidenced in figure 5 and 6, the mean value of S/N ratios increases with an increase in applied voltage from 65-85 V. In case of electrolyte concentration as its value increases from 15-20% there is small increase in the mean value of S/N ratio but when electrolyte concentration increases from 20-25% the mean value of S/N ratio decreases. In case of abrasives the when graphite was used the increase in mean value of S/N ratio was more as compared to silica. When feed rate increases from 0.4 to 0.8 rpm there was no significant change in the mean value of S/N ratio but as feed rate increases from 0.8 to 1.2 rpm there was large decrease in the mean value of S/N ratio.

![Main Effects Plot for Means](image2.png)

**Figure 5: Effect Plot for Means of MR**
5 Conclusions

This paper presents a review on the effective parameters in Electro-chemical Discharge Machining. Based on the study of various research papers and following broad conclusions can be drawn:

1. The study was very useful in understanding the basis of the ECDM process as well as the problem faced during machining in ECDM.
2. The machining performance of ECDM depends on the stability and uniformity of gas film around the tool.
3. The most influencing factor found through the experiment was the feed rate of work.
4. The optimum result obtained was 0.4 rpm from material removal rate point of view.
5. The most suitable electrolyte found was 25% by weight, from highest material removal point of view.
6. The use of abrasive powders enhances the material removal as the graphite powder gave high material removal as compared to silica powder.
7. Electrolyte concentration is a secondary factor of concern affecting the MR.
8. The material influencing parameter is voltage but to increase the performance of ECDM, other factors should also be considered like tool geometry, polarity, addition of abrasives in the electrolyte etc.
9. Less work has been done on ceramics of semi conducting materials like composites.
10. The ECDM has capability to machine non-conductive materials with better accuracy but proper selection and optimization of parameters is necessary.

References

1. Kurafuji, H. (1968). Electrical discharge drilling of glass. CIRP Ann, 16(1), 415-419.
2. R. Wuthrich and V. Fascio (2005), Machining of non-conducting materials using electrochemical discharge phenomenon—an overview, International Journal of Machine Tools & Manufacture 45 (2005) 1095–1108.
3. Bhattacharya B, Doloi B. N., Sorkhel S. K., “Experimental Investigation into ECDM of Non Conductive Ceramic Materials”, Journal of Material Processing Technology, 95, 1999, 145-154.
4. Jain, V. K., & Adhikary, S. (2008). On the mechanism of material removal in electrochemical spark machining of quartz under different polarity conditions. Journal of materials processing technology, 200(1-3), 460-470.
5. Didar, T. F., Dolatabadi, A. and Wüthrich, R. (2009). Local hardness and density variation in glass substrates machined with Spark Assisted Chemical Engraving (SACE). Materials Letters, 63 (1), 51-53.
6. C. S. Jawalkar and Apurbba Kumar Sharma , Micromachining with ECDM: Research Potentials and Experimental Investigations, International Journal of Mechanical and Aerospace Engineering 6 2012
7. Jain, V. K., & Priyadarshini, D. (2014). Fabrication of microchannels in ceramics (quartz) using ECSM. Journal of Advanced Manufacturing Systems, 13(01), 5-16
8. Charak, A., & Jawalkar, C. S. (2017). Technological Landscaping on Electro Chemical Discharge Machining of Non-Conducting Materials. *I-Manager’s Journal on Material Science*, 5(3), 31.

9. I Basak and A Ghosh, Mechanism of Spark Generation during ECDM, a Theoretical Model and Experimental Verification. *Journal of Material Processing Technology* 62 (1996) 46-53

10. C. S. Jawalkar and Apurbba Kumar Sharma, A Review on EDM, ECDM And Its Variant Processes, *International Conference on Agile Manufacturing Systems* 2011, Agra, India.

11. Yang, C.T., Song, S.L. and Yan, B.H. (2006) "Improving machine performance of wire ECDM by adding SiC abrasives to electrolyte", *International Journal of Machine Tools and Manufacture*, Vol. 46, No. 15, pp.2044–2050.

12. M.S. Han, B.K. Min, S.J. Lee, J. “Micromachining Micro engineering”, 19 (2009) 1.

13. Y.S. Laio, L.C. Wu and W.Y. Peng, A study to improve drilling quality of electrochemical discharge machining (ECDM) process. *The Seventeenth CIRP Conference on Electro Physical and Chemical Machining (ISEM)*, Procedia CIRP 6 (2013) 609 – 614

14. Basak, I., & Ghosh, A. (1997). Mechanism of material removal in electrochemical discharge machining: a theoretical model and experimental verification. *Journal of materials processing technology*, 71(3), 350.

15. Liu, J. W., Yue, T. M., & Guo, Z. N. (2010). An analysis of the discharge mechanism in electrochemical discharge machining of particulate reinforced metal matrix composites. *International Journal of Machine Tools and Manufacture*, 50(1), 86-96.

16. Paul, L., & Hiremath, S. S. (2016). Improvement in Machining Rate with Mixed Electrolyte in ECDM Process. *Procedia Technology*, 25, 1250-1256.

17. C. S. Jawalkar and Apurbba Kumar Sharma, Investigations on performance of ECDM process using NaOH and NaNO3 electrolytes while micro machining soda lime glass. *International Journal Manufacturing Technology and Management*, Vol. 28, Nos. 1/2/3, 2014.

18. Goud, M., Sharma, A. K., & Jawalkar, C. (2016). A review on material removal mechanism in electrochemical discharge machining (ECDM) and possibilities to enhance the material removal rate. *Precision Engineering*, 45, 1-17.

19. V. K. Jain and D. Priyadarshini “Fabrication of Micro Channels in Ceramics (Quartz) Using Electrochemical Spark Micro Machining (ECSM)”, *Proceedings of Global Engineering, Science and Technology Conference* 3-4 October 2013, Bay View Hotel, Singapore, ISBN: 978-1-922069-32-0.

20. Kulkarni A., Sharan R. and G. K. Lal., An experimental study of discharge mechanism in electro-chemical discharge machining. *International Journal of Machine Tools & Manufacture*, Vol.42, 2002, 1121–1127.

21. Laio, Y. S., Wu, L. C., & Peng, W. Y. (2013). A study to improve drilling quality of electrochemical discharge machining (ECDM) process. *Procedia CIRP*, 6, 609-614.

22. Dhanvijay, M. R., & Ahuja, B. B. (2014). Micromachining of ceramics by Electrochemical Discharge process considering stagnant and electrolyte flow method. *Procedia Technology*, 14, 165-172.

23. Paul, Lijo, and Somashhekar S. Hiremath. "Evaluation of process parameters of ECDM using grey relational analysis." *Procedia Materials Science* 5 (2014): 2273-2282.

24. Bhondwe, K. L., Yadava, V., & Kathiresan, G. (2006). Finite element prediction of MRR due to electro-chemical spark machining. *International Journal of Machine Tools and Manufacture*, 46(14), 1699-1706.

25. Kuo, K. Y., Wu, K. L., Yang, C. K., & Yan, B. H. (2013). Wire electrochemical discharge machining (WECDM) of quartz glass with titrated electrolyte flow. *International Journal of Machine Tools and Manufacture*, 72, 50-57.

26. Yang, C. K., Cheng, C. F., Mai, C. C., Wang, A. C., Hung, J. C., & Yan, B. H. (2010). Effect of surface roughness of tool electrode materials in ECDM performance. *International Journal of Machine Tools and Manufacture*, 50(12), 1088-1096.

27. B. Bhattacharyya, B. Doloi, S. Mitra, S.K. Sorkhel, “Experimental analysis on the electrochemical discharge machining (ECDM) system for advanced ceramics”, *International Conference on Precision Engineering, ICPE, Taipei, Taiwan*, 1997, 715-720.