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# Mathematical modelling of MRR and Heat flux using FEA in the ECDM process

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***Abstract - Electrochemical discharge machining (ECDM) is a non-conventional technology which is mostly applied for the effective and economical micro- machining of several non-conductive materials. Most of the application of ECDM is in machining nonconductive materials, although some authors have also tried machining conductive materials. This paper attempts to mathematical modelling for MRR and develop a Finite element simulation model based on heat generation in spark region to evaluate material removal rate (MRR) of quartz material. The first one is the development of a thermal finite element model to estimate the temperature distribution within the heat-affected zone (HAZ) of series of spark on the workpiece. In ECDM the heating from the spark zone is considered as a Gaussian distribution on the surface of the workpiece. The calculation of MRR is based on melting and evaporation of the material due to high temperature of the spark.***

***Keywords- Electrochemical discharge machining, Finite element analysis, Material removal rate, Gaussian heat generation, Heat affected zone.***

## 1. Introduction

The electrochemical discharge machining (ECDM) have many applications for machining non-conducting engineering materials such as quartz, glass. The perspective of manufacturing is changing in the recent times [1]. The micro-slots fabricated needs secondary process for their surface finishing[2]. ECDM uses both spark action and chemical action for removal of material. Although sparking action has a major contribution to the material removal but fine material removal is done by chemical action which provides good surface finish. It is observed that toxic fumes produced during machining leads to partial suffocation[3].The phenomenon of ECDM was first reported by Kura fuji and Suda [4] in 1968 and they termed it as electrical discharge drilling of glass. An attempt was made to develop a theoretical model by Basak and Ghosh 1996 [5] for spark discharge phenomenon by considering inductance as an important parameter. Bhattacharyya et al [6] did an experimental investigation to found the influence of voltage and electrolyte concentration on material removal rate (MRR) they tried to stabilize the arc by using various tool shapes. The mechanism of gas film formation is not fully understood and still debatable. Although some authors claim that the local heating of the electrodes causes the vaporization of the electrolyte in contact with it and results in the formation of gas. Vogt H [7] explained that the bubbles formed due to electrochemical action and the effect of wettability of anode as the main reasons for the gas film formation. Nguyen et al [8] tried to investigate the effect of feed rate and electrolyte level on stability and generation of the arc. Paul and Hiremath [9] tried to generate micro-feature with mixed electrolyte and then compared the results with single electrolyte. Cao et al. [10] demonstrated the potentials of ECDM for micromachining of glass by fabricating three-dimensional microstructures of around 80 mm in size. Cs Jawalkar [11] studied material removal rate (MRR) of soda lime glass, optical glass, and borosilicate glass using NaCl and NaOH electrolytes.

Machining of metal matrix composites with water-based emulsion added to NaOH electrolyte was reported by Liu et al. [12] with maximum MRR of 49 $mm^3$/min. In case of borosilicate glass, the maximum MRR of 5.6 mg/min was reported by Gautam and Jain [13].

In ECDM, the ECM process generates bubbles at the tool electrode and material is removed by thermal erosion. A high temperature is generated due to a high-density thermal energy discharge, which leads to melting and vaporisation (thermal erosion) (Basak and Ghosh, 1996; Jain et al., (1999) [14]. The material, which is not removed, gets re-solidified over the machined surface, which is called a 'recast' layer. The maximum temperature produced during an electrical discharge is of the order of magnitude $10^4$ K so formation HAZ to happen as reported by Yang et al. [15] they studied the effect of wettability on gas film formation and reported that tungsten carbide tool has the lowest wear on its edge where the current density is considered maximum. Kro¨tz et al.[16] studied the heat-affected zone for a single discharge of electrochemical arc machining by developing a 2D model to simulate the heat transfer into the work-piece. Goud and Sharma [17] developed a FEA model considering heat generation in three-dimensional Gaussian spark region and predicted MRR on silica glass and alumina, these results are compared with the result available from the experiment.

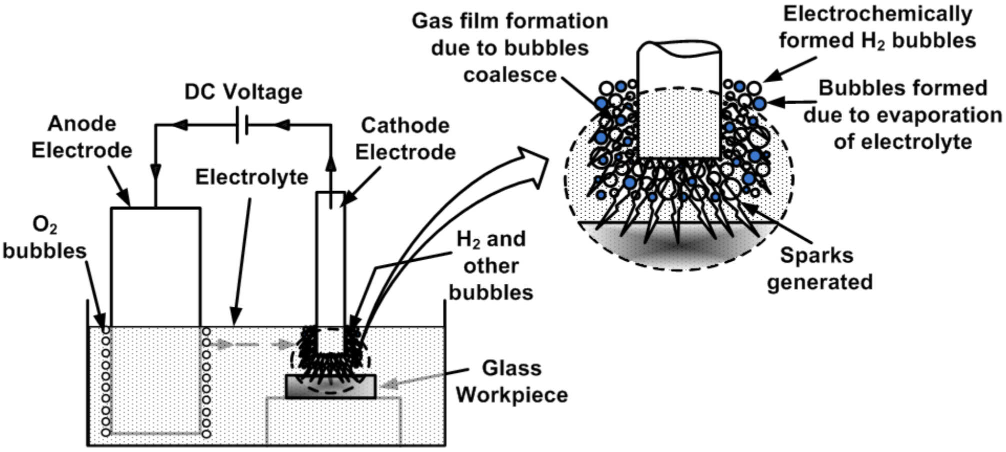


**Fig 1.1 Diagram of ECDM (Goud and Sharma (2016))**

In ECDM process the work piece is dipped in an appropriate electrolytic solution usually sodium hydroxide or potassium hydroxide. A constant DC voltage is applied between the machining tool or tool-electrode. The electrode which is made cathode is allowed to just touch the surface of electrolyte to have a small gap between workpiece and electrode. The electrode is very small in size and is made cathode while anode which is very big in size is dipped in the electrolyte.
The reactions taking place in cathode and anode are as follows. (Bhattacharyya et al. (1999)).

$$2H_2O + 2e^- \rightarrow 2(OH)^- + H_2$$

$$M \rightarrow M^+ + e^-$$

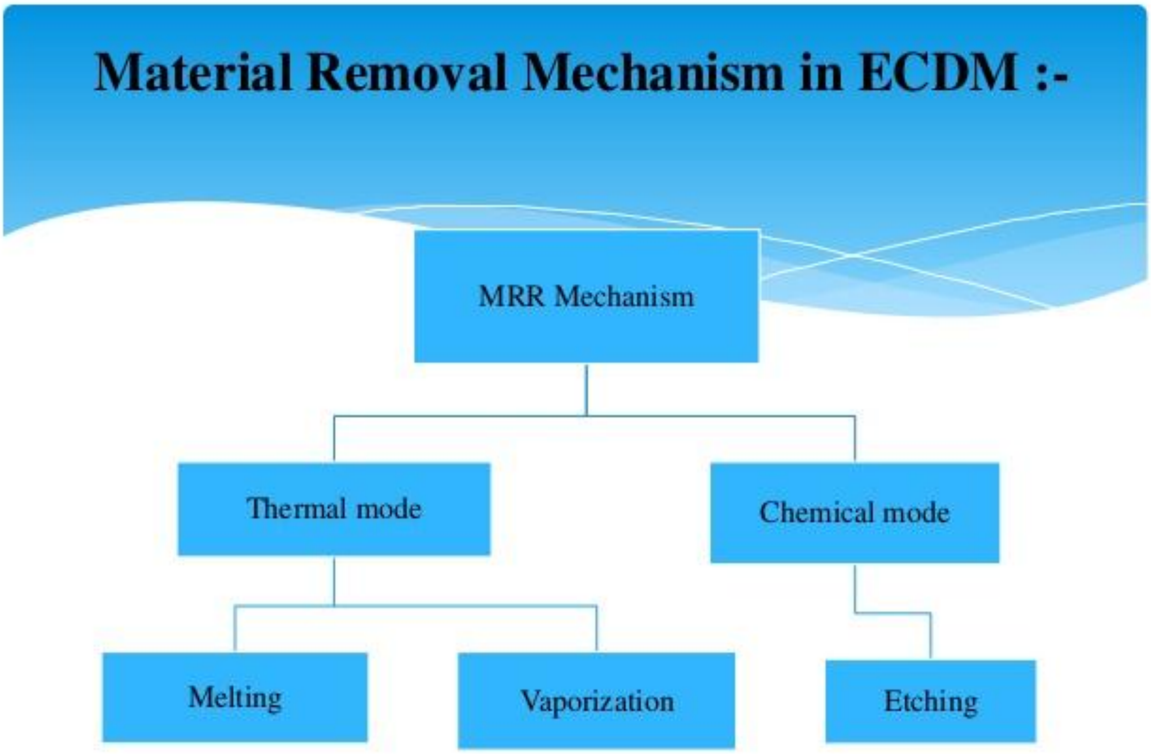

Material Removal Mechanism in ECDM :-

**Fig 1.2 Material removal rate mechanism in ECDM process**

## 2. Literature Review

The phenomenon of ECDM was first reported by **Kurafuji and Suda (1968)** they used the name electrical discharge drilling. Cook et al. (1973) suggested a new name for the process as discharge machining of non-conducting materials, saying that the process described by Kurafuji and Suda is different from EDM and ECM. They applied the process to broad range of non-conductive materials and further studied the effect of the electrolyte.

**Basak and Ghosh (1996)** attempted to develop a theoretical model for spark discharge phenomenon by considering inductance as an important parameter. The author tried to enhance the possibility of capability of the process by using various input parameters. The discharging phenomenon was analysed as a switching process between the tool and the electrolyte. The experimental and theoretical results indicated the significant increase in MRR can be obtained. Figure 2.1 represents V-I characteristics during various zones of voltages and different bubble distribution. An attempt was also made to estimate the critical voltage and critical current to initiate the sparking phenomenon between electrode and electrolyte Figure 2.2 represents the bubble distribution at critical voltage and current with idealized switching phenomenon

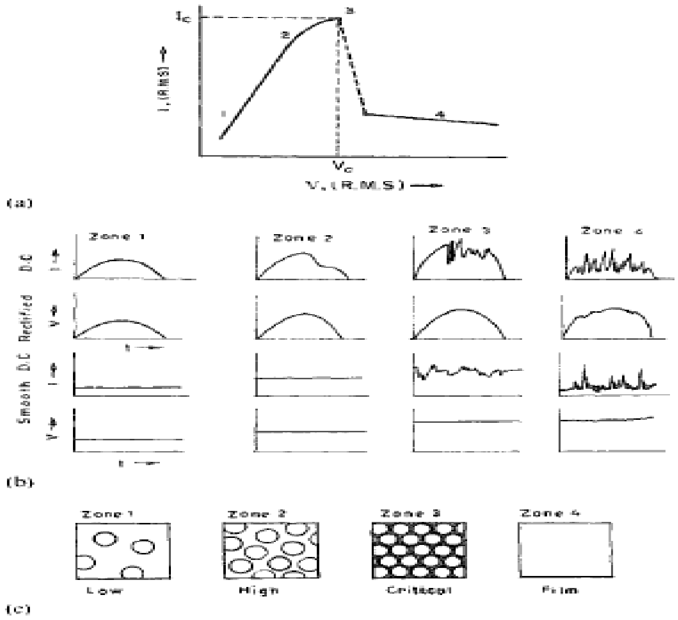


**Figure 2.1 (a) Voltage-current relationship for typical ECD cell. (b) Traces of voltage and current for different values of applied potential. (c) Distribution of bubbles on the tool electrode for different applied voltages (Basak and Ghosh (1996))**

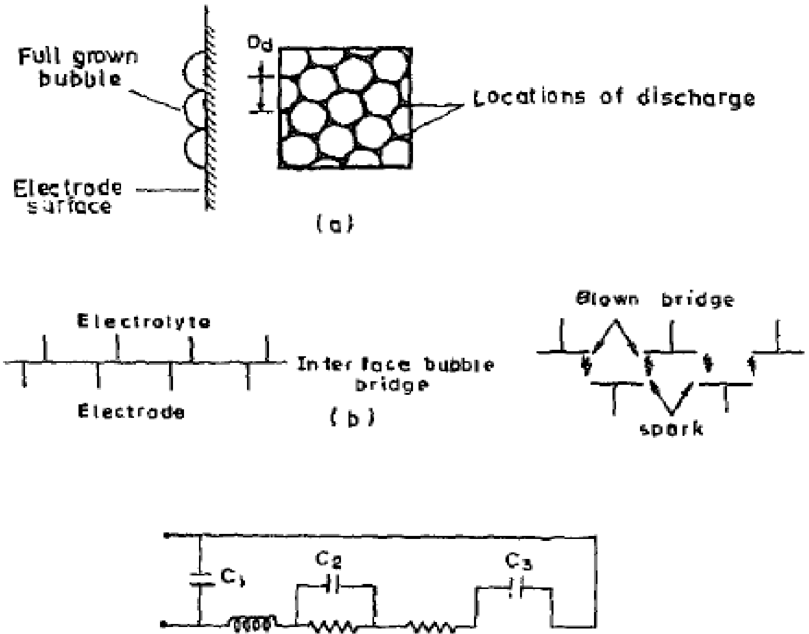


**Figure 2.2 (a) Discharge locations with the bubble distribution at critical condition. (b) Idealised switching-off situation. (c) Idealised equivalent circuit at discharge (Basak and Ghosh (1996))**

**Bhattacharyya et al. (1999)** did an experimental investigation to found the influence of voltage and electrolyte concentration on material removal rate (MRR) they tried to stabilize the arc by using various tool shapes. Many experiments were also conducted on the ceramic components using pulsed DC voltage and found out that at low voltage MRR is low but at high voltage and high electrolyte concentration greater overcut was obtained. It was also found out that at high voltage micro cracks and other defects were generated on the machined surface. Figure 2.3 represents different geometrical shapes used for experimentation. at different electrolyte concentration while Figure 2.4 represents the variation of MRR with electrolyte concentration at different voltages

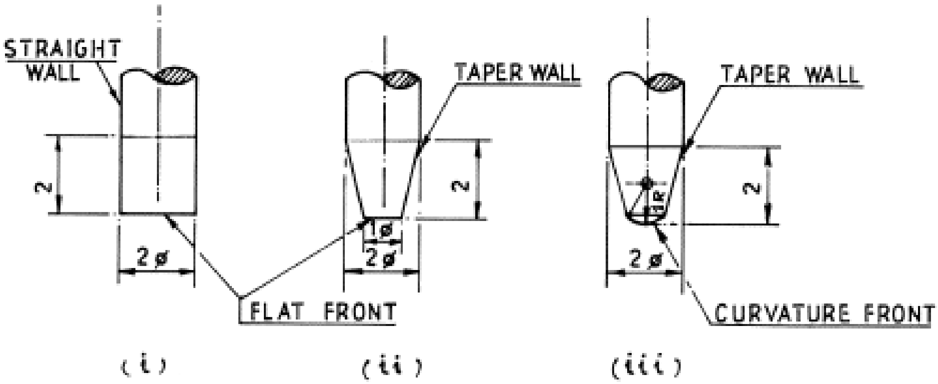


**Figure 2.3 Different geometrical shapes of the tool tip (Bhattacharyya et al. (1999))**

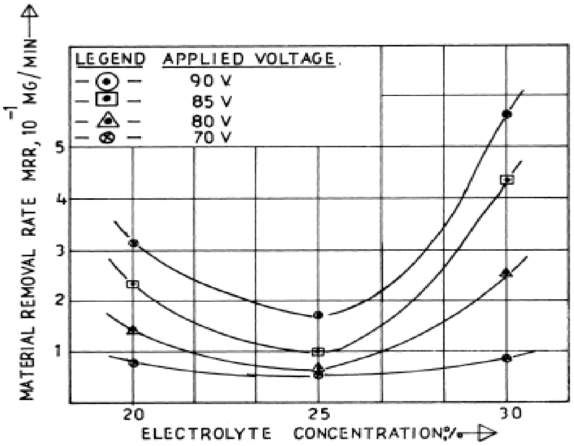


**Figure 2.4 Effect of electrolyte concentration on MRR for silica glass (Bhattacharyya et al. (1999))**

**Yerokhin et al. (1999)** claimed that the local heating of the electrodes causes the vaporization of the electrolyte in contact with it and results in the formation of gas.

**Vogt (1999)** explained that the bubbles formed due to electrochemical action and the effect of wettability of anode as the main reasons for the gas film formation.

**Nguyen et al. (2015)** tried to investigate the effect of feed rate and electrolyte level on stability and generation of the arc and found out that low electrolyte levels results in low resistivity between the electrodes and high discharge current value. Figure 2.5 shows two holes drilled at different electrolyte level

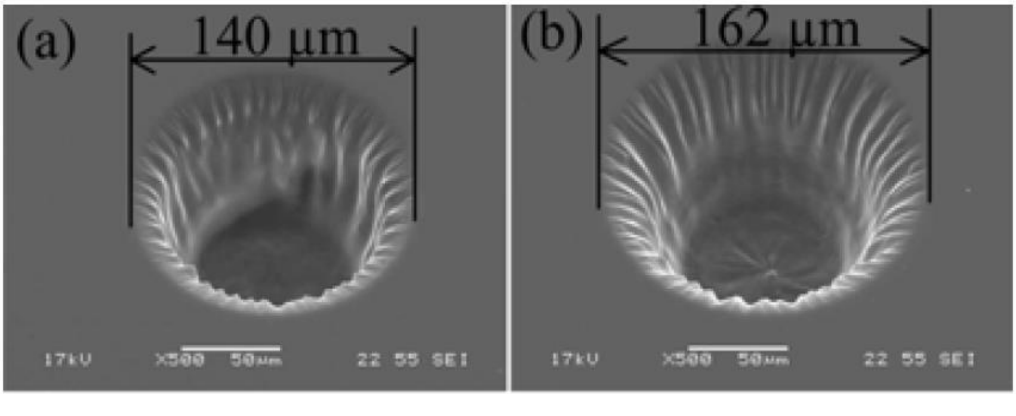


**Figure 2.5 Micro hole machined with different electrolyte levels (a) 300µm (b) 1000 µm (Nguyen et al. (2015))**

**Jain and Chak (2000)** attempted to perform trepanning on alumina and glass with ECDM and reported a decrease in MRR with an increase in depth. The author also reported that beyond certain value of electrolyte temperature, ECDM process starts deteriorate. Figure 2.7 represents the relation of MRR with supply voltage during trepanning

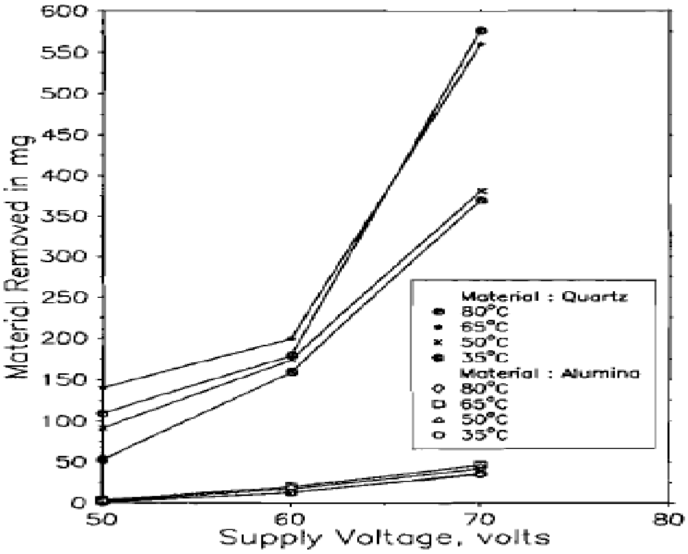
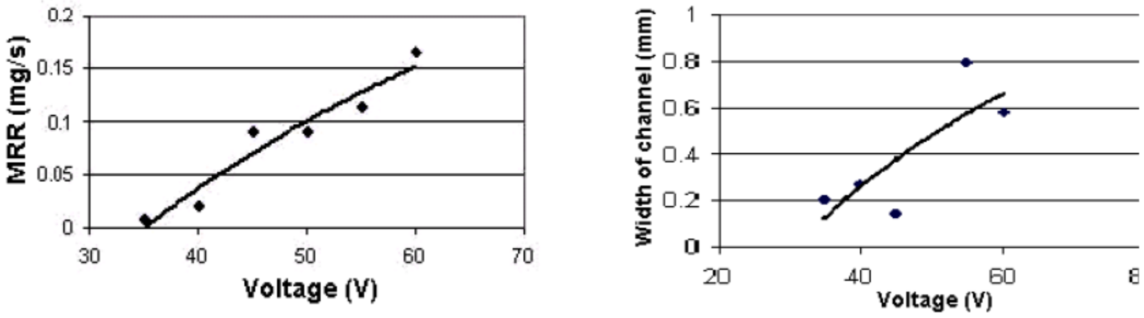


**Figure 2.6 Relation of supply voltage with MRR in quartz and alumina during trepanning (Jain and Chak (2000)**

**Jain and Priyadarshini (2013)** investigated the machining of the microchannel in quartz and studied the influence of voltage on, the width, depth and heat affected zones on microchannel and found that as the voltage increases the MRR increases the width of channel increases, the width of HAZ increases and depth becomes non-uniform and reported a minimum width of 144µm. the effect of voltage on MRR and channel width is shown in Figure 2.8. SEM image of quartz microchannel is also shown in the figure 2.9



(a) (b)

Figure 2.7 Effect of voltage on (a) MRR and (b) width of channel (Jain and Priyadarshini (2013))

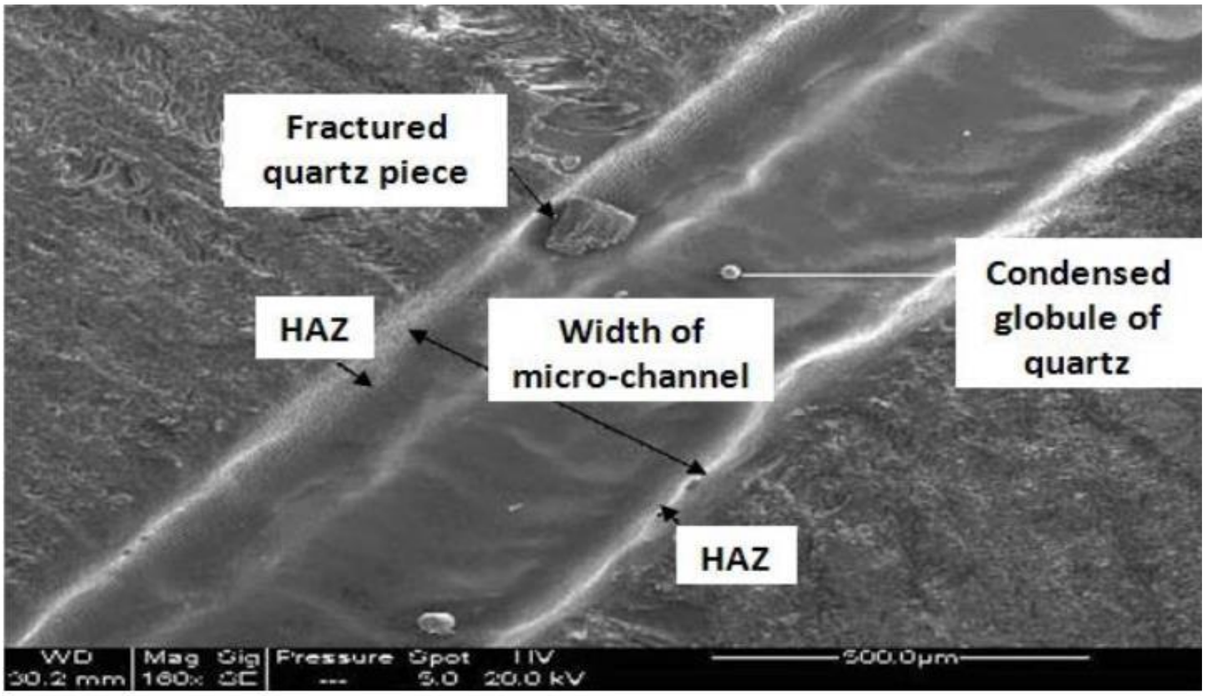


**Figure 2.8 Magnified view of quartz microchannel (Jain and Priyadarshini (2013))**

**Xu et al. (2018)** presented the analytical analysis of magneto hydrodynamic (MHD) effect and to analyse the mechanism of magneto hydrodynamic effect in ECDM. They used a high speed camera to record the formation of gas film on the tool. The high speed camera image of bubble movement is shown in Figure 2.11 They showed that MHD effect induced by the magnetic field improved electrolyte circulation and obtaining higher machining efficiency.

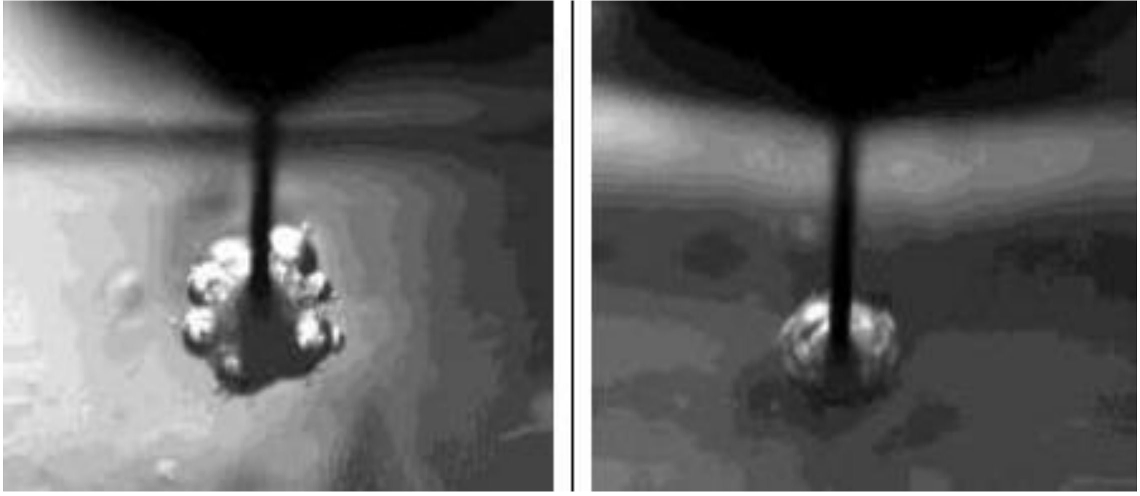


**Figure 2.9 High speed camera images of electrolysis bubble movement in ECDM (a) without and (b) with MHD effect (Xu et al. (2018))**

## 3. Literature review in ECDM Finite element analysis

Several authors have tried to correlate different parameters to predict MRR using various tools such as Finite element analysis by Jain et al. (1999), Taguchi by Mitra et al. (2014), Response surface by Paul and Hiremath (2013), Fuzzy logic by Skraalak et al. (2004) and Artificial neural network by Sathisha et al. (2014) Every tool gives result considering some of the assumptions and no theory is completely generalized and widely accepted till present.

**Bhondwe et al. (2006)** carried out FEA two-dimensional thermal analysis and predicted MRR and compared the results with the previous experimental work to validate the mathematical model. Figure 2.15 and 2.16 represents the variation of MRR with electrolyte for alumina and soda-lime glass respectively.

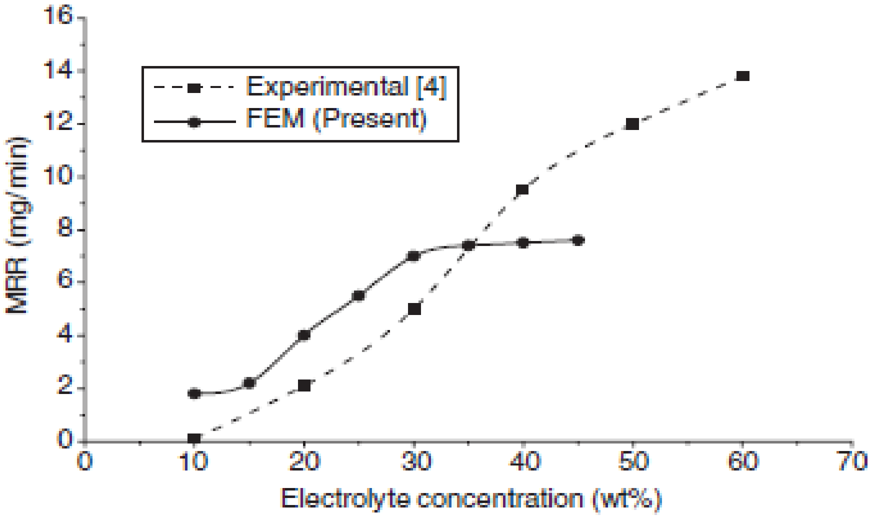


**Figure 3.1 Variation of MRR during ECSM of soda lime glass workpiece (Bhondwe et al. (2006))**

**Wei et al. (2011)** gave the finite element model for discharge regime where most of the metal removal takes place

**Jain et al. (1999)** developed the relationship between thermal conductivity and electrolyte concentration and then developed their finite element model.

**Goud and Sharma (2016)** developed a finite element thermal model considering heat generation in three-dimensional Gaussian spark region and predicted MRR on silica glass and alumina, these results were then compared with the result available from the experiment and found to be in agreement

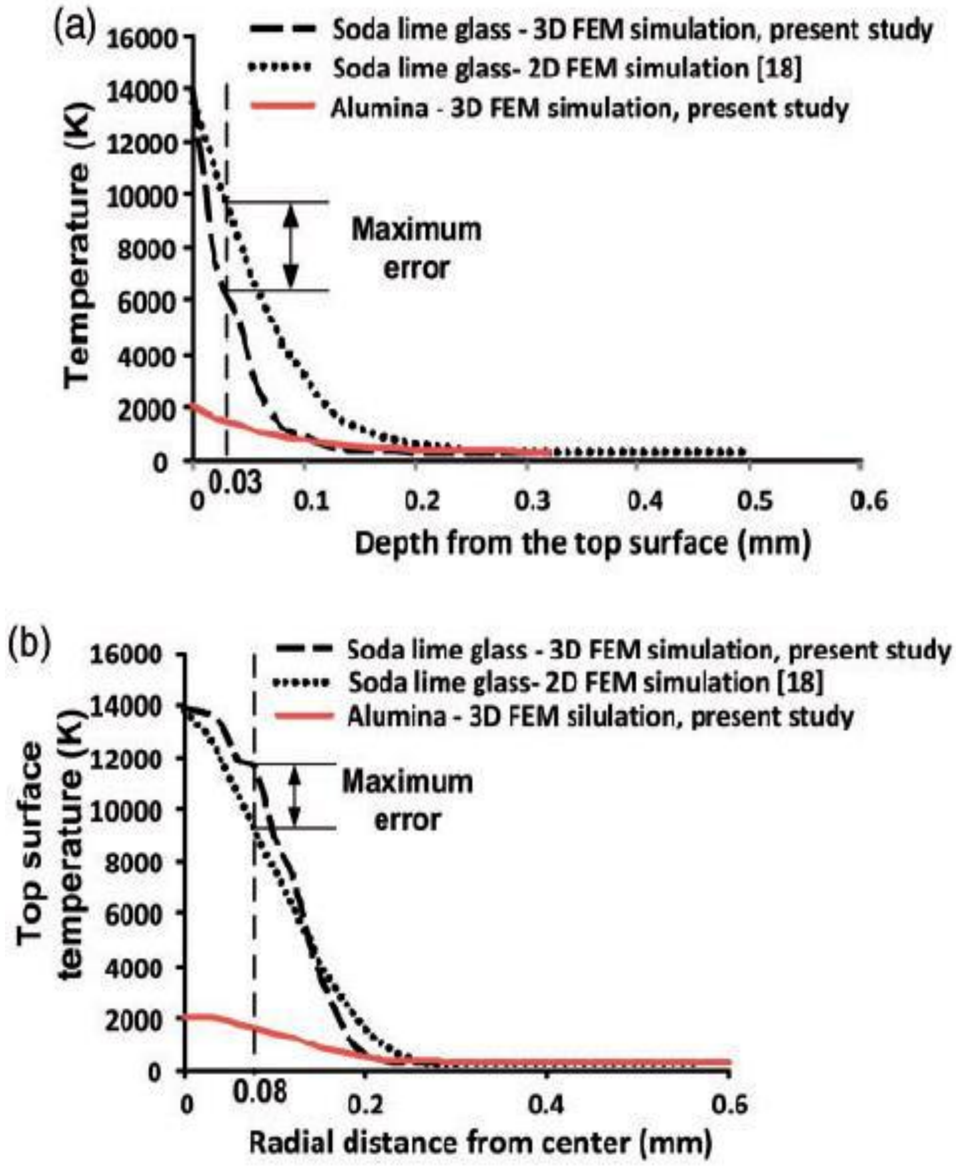
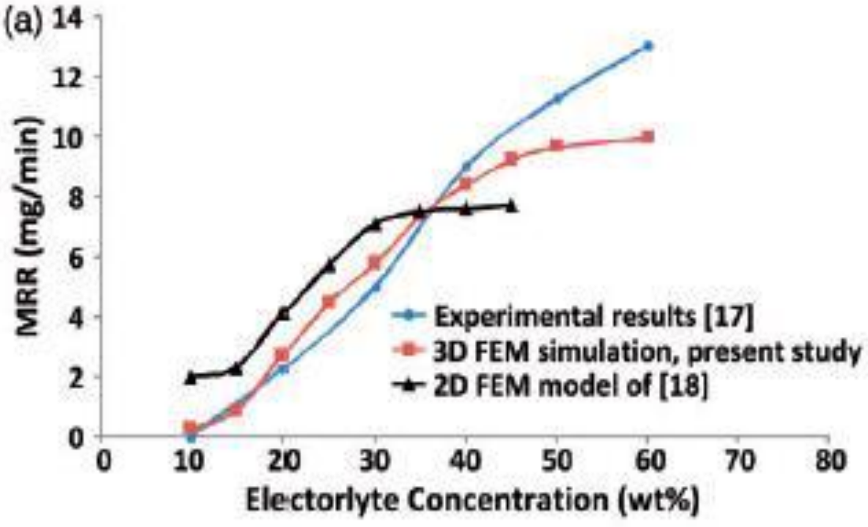


**Figure 3.2 Temperature distribution in workpiece (a) along the depth from top surface; (b) along the radial direction (Goud and Sharma (2016))**



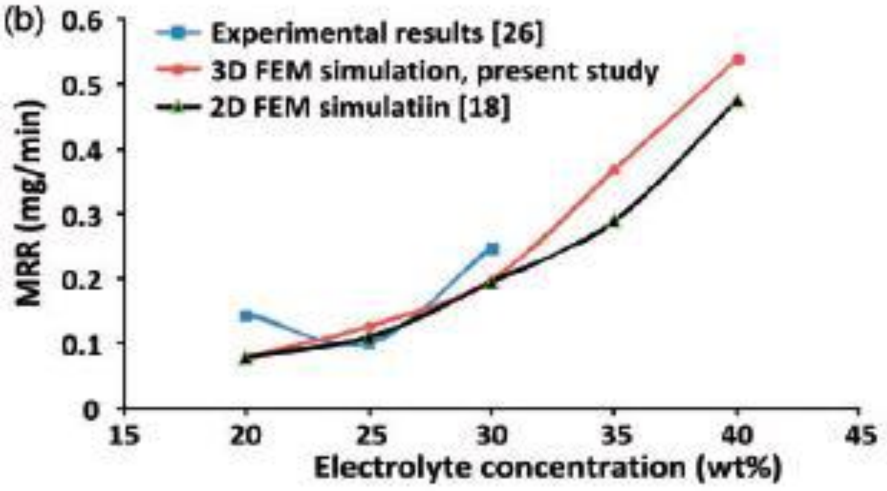


**Figure 3.3 Comparison between MRR of experimental and simulation results (a) Soda lime; (b) alumina (Goud and Sharma (2016)**

## 4. Research Gap

- Most of the analysis carried out for simulation of ECDM were done without giving due consideration to convection heat transfer effect on the sparking surface where boiling of electrolyte takes place and some of the heat is lost.
- FEA analysis for quartz material has not been performed till date.
- The effect of machining due to chemical action on material removal rate has also not been explored and not included in the simulation
- No study has been done to further evaluate the magneto hydrodynamic effect on the bubble formation and dynamics.
- No study is done to compare different FEA techniques used for the estimation of MRR in ECDM process.

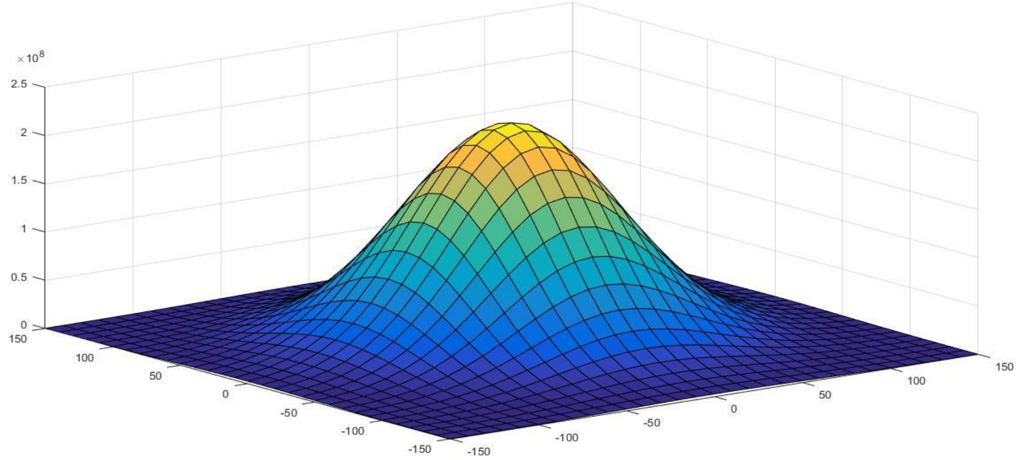


**Fig. 4.1 Gaussian distribution of heat flux**

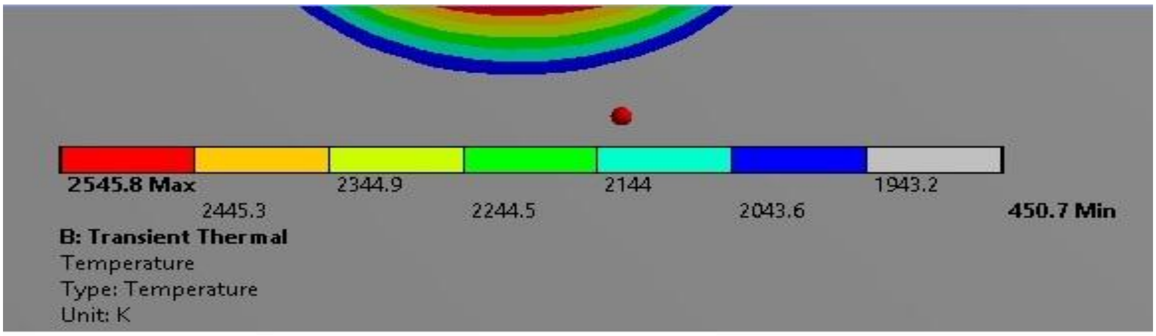


**Figure 4.2 Cut section view of the temperature distribution in FEA model for quartz at 40V**

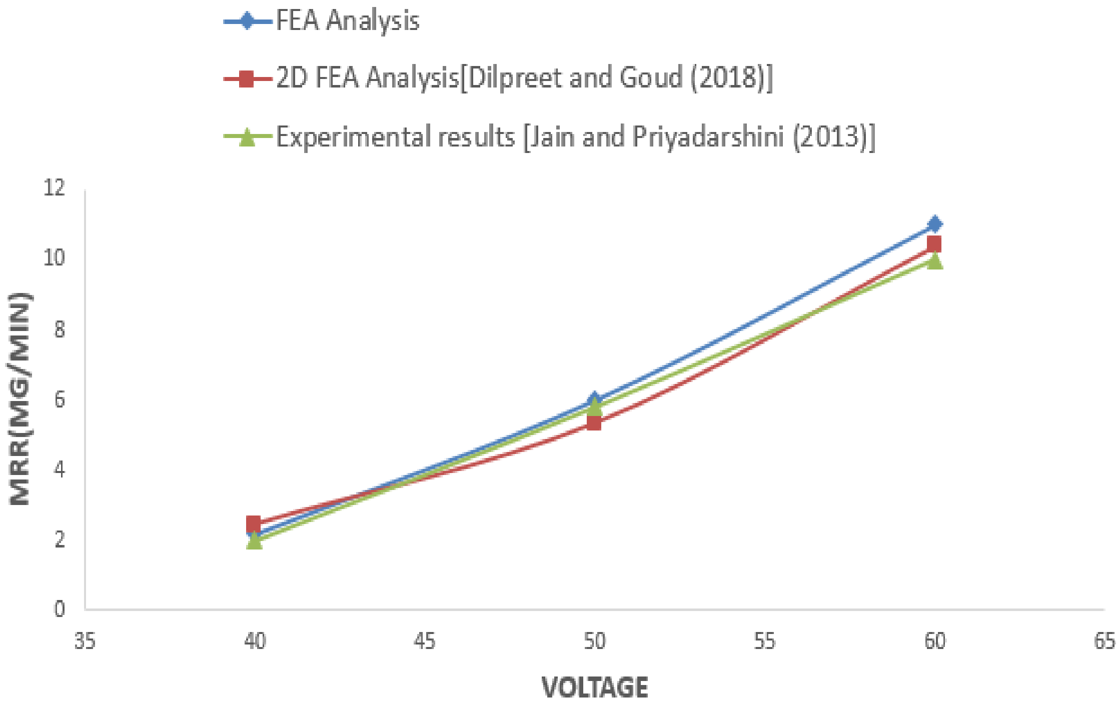


**Figure 4.3 comparison of MRR from FEA analysis with MRR from experimental results (Jain and Priyadarshini [18] (2013) and Mudimallana Goud [19])**

## 5 Conclusions

The electrochemical discharge machining (ECDM) process can be utilised effectively for the machining of non-conductive materials such as quartz, ceramics and advanced composites. The material removal during the machining of non-conducting ceramic workpiece in the ECDM process mainly takes place due to spark discharge action across the gas bubble layers formed on the workpiece surface. At low applied voltage, the MRR is very low, but at higher voltage and higher electrolyte concentration, a higher MRR can be achieved.

The results obtained by the 3D FEM simulation analysis of ECDM process are matching with the experimental results taken from the literature under the same machining conditions. However, there exists a little difference between them due to the assumptions regarding spark radius, ejection efficiency, energy partition, etc.

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