STUDY ON EFFECTIVE PROCESS PARAMETERS: TOWARD THE BETTER COMPREHENSION OF ECDM PROCESS

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Abstract: The applications of advanced engineering materials such as glass, quartz, ceramics, and composites are escalating in the field of Micro-electro Mechanical system owing to their wide scope of utilization in product miniaturization. Electro-Chemical Discharge Machining (ECDM) is a proven technology for machining these materials with micro-features by combining the machining features of Electro-Discharge Machining (EDM) and Electro-chemical Machining (ECM) processes simultaneously. This machining process has drawn significant interests as it enacts a platform for new opportunities and applications owing to the potential of machining materials in a more efficacious and productive way. In this present paper, an overview of the ECDM process and influence of the process parameters such as Electrolyte parameters, Electrical parameters, Tool electrode parameters, etc. have been carried out on the response parameters such as Material Removal Rate (MRR), Surface Finish and Tool Wear. The experimental study has been performed to evaluate the influence of process parameters on MRR using one factor at a time (OFAT) approach. Results revealed that MRR increases with the increase in applied voltage and electrolyte concentration due to an increase in the spark intensity. It has been concluded that process parameters have a significant impact on the efficacy of the machining process and selection of its optimum range is very crucial for attaining high-quality characteristics especially during machining repeatability. Moreover, areas of future research in electrochemical discharge machining are highlighted.
Key words: Micro machining, ECDM, Applied Voltage, Spark, Material removal Rate, Thermal Cracks

1. INTRODUCTION

The demand of micro-features on advanced materials started with its increased demand in nuclear, medical, aviation and other industries which led to the miniaturization of the products (Altan et al., 2001; Jianhu and Xing, 1991; Xinghua et al., 2002; Tolke et al., 2012). Furthermore, materials which are ‘difficult to machine’ by conventional method such as non-conductive materials, brittle and hard materials etc., also brings a challenge in the field of micromachining as cutting forces are associated with conventional machining (Uriarte et al., 2006; Wang et al., 2015; Huang, 2003). This leads to the development of the more innovative and reliable technique for micro-machining of these ‘difficult to machine’ materials. Glass, quartz, ceramics, composites, etc are some of the examples of these materials. Various researchers reported that numerous non-conventional machining processes are available which can be utilized for machining non-conductive materials such as (LBM) laser beam machining (Yilbas et al., 2016; Mahamani and Chakravarthy, 2017), Ultrasonic machining (USM) as explained by (Singh and Singhal, 2017; Guzzo et al., 2004) and Electro-discharge machining (EDM) as explained by (Zaripov and Ashurov, 2011; Wei et al., 2013) etc. Besides, several intrinsic problems are there which seems to be attached with these machining processes such as poor surface finish, high rate of tool wear, high heat-affected zone (HAZ) and low removal rate of the work material (Mahamani and Chakravarthy, 2017; Singh and Singhal, 2017; Zaripov and Ashurov, 2011; Wei et al., 2013; Yilbas et al., 2016; Chen et al., 1996). The development of the ECDM process is the result of confronting these limitations and recognized as the most prosperous hybrid machining process, which blends the features of ECM and EDM for machining non-conductive materials. Material removal in ECDM takes place due to thermal erosion primarily as explained by (Jahan et al., 2011; Kumar et al., 2010; Kolhekar and Sundaram, 2018) and chemical etching action (Rabbo and Boden, 1979; Spieser and Ivanov, 2013; Ghosh, 2016). It is noteworthy to see that the combined mechanism of material removal in ECDM produces a much higher removal rate of the material when compared to individual ECM or EDM as demonstrated in (De Silva, 1988; Crichton and Mcgeough, 1985; Jain and Chak, 2002). It is also known by different names like Electrochemical arc machining (Critchon et al., 1985), Electrochemical discharge machining (Allesu et al., 1992), Electrochemical spark machining (Tandon et al.,1990), spark assisted chemical engraving (Fascio et al., 2004) and Electro erosion dissolution machining (Khairy and Mcgeough, 1990). This process has very crucial applications in the micro-fabrication of three-dimensional features on glass material which is the key component used in micro-electro-mechanical systems (MEMS). Other modern industries such as micro-biological laboratories, astronomy, kitchenware, etc. preferred advanced materials like glass, ceramics, etc. owing to their peculiar properties such as resistance to a chemical substance, transparency, compatibility with bio tissues and low coefficient of thermal expansion. Some of the examples of ECDM machining potential are shown in Figure 1 which describes the three-dimensional micro-fabrication of Pyrex glass machined layer-by-layer in micro-milling operation. A depth of 50μm was successfully obtained with a tool feed rate of 1000μm/min for a single layer. The whole process was repeated again and again till the final desired depth was not attained as demonstrated in Zheng et al. (2007).

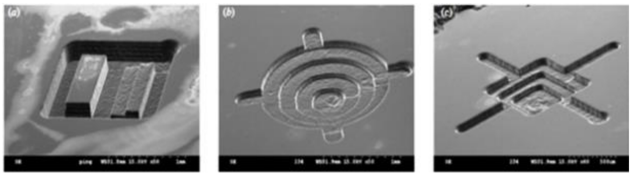

Fig.1. 3D microstructures of Pyrex glass made by ECDM [96]

2. ECDM WORKING PRINCIPLE

The ECDM process consists of an electrolytic cell, electrolyte, tool electrode (i.e. cathode), auxiliary electrode (i.e. anode) and work material. The tool electrode is positioned normal above the work material at a small distance (or machining gap). Both the electrodes are immersed in an electrolyte (generally alkaline electrolytes like NaOH, KOH, etc.) and separated by a distance of few centimeters (or Inter-electrode gap) as shown in Figure 2. A pulsed or continuous direct current (DC) power supply is applied between two electrodes i.e. anode and cathode to complete the circuit (or to trigger electrolysis) which further helps in the formation of tiny hydrogen gas bubbles at the cathode and tiny oxygen bubbles at the anode respectively.

The formation of these tiny bubbles (oxygen and hydrogen) occurs due to electrochemical reactions and ohmic heating of the electrolyte. As the rate of formation of hydrogen gas bubbles across the tool electrode becomes higher than the rate of formation of bubbles floating on the electrolyte, then these tiny bubbles start coalescence physically with each other within the electrolyte to form a big size bubble which further transformed into hydrogen gas film at the vicinity of the tool electrode as shown in Figure 3(a) (Bhattacharya et al., 1999) where Figure 3(b) represents stepwise spark generation mechanism in ECDM process. This hydrogen gas film behaves as an insulator around the tool (also known as tool blanketing) which abruptly terminates the flow of electric current and generates immense electric field over the dielectric film produced between tool and electrolyte. This leads to the generation of electrical spark (or discharge) at the interface of the tool electrode and electrolyte due to the electric breakdown of the dielectric film. Thereafter, workpiece is placed just underneath the tool electrode tip at a very small gap (in microns) by using a controlled fixture.

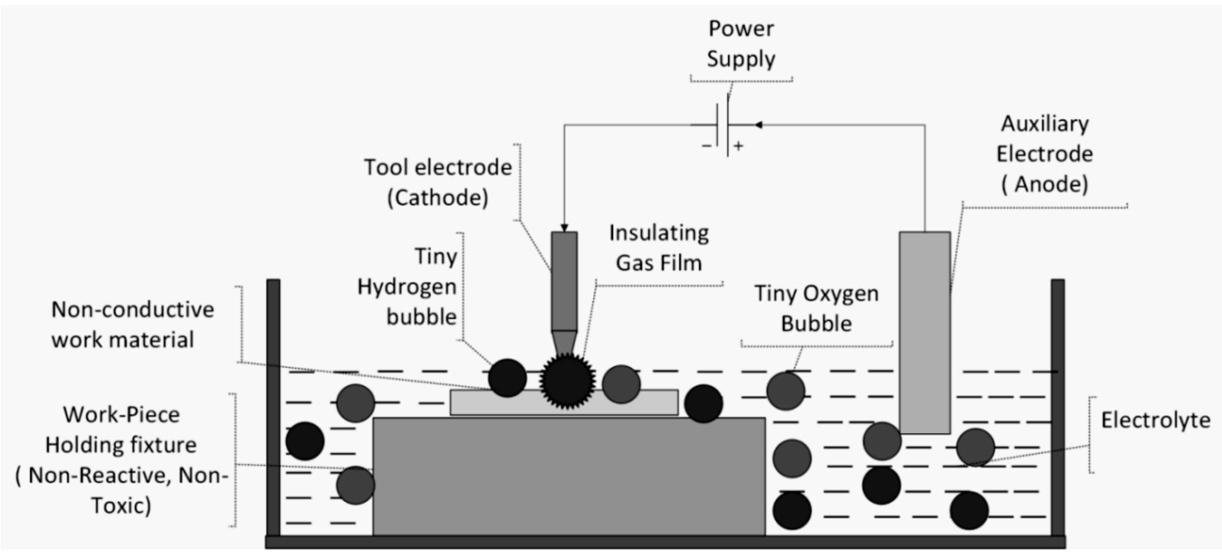

Fig. 2. Principal Diagram of ECDM

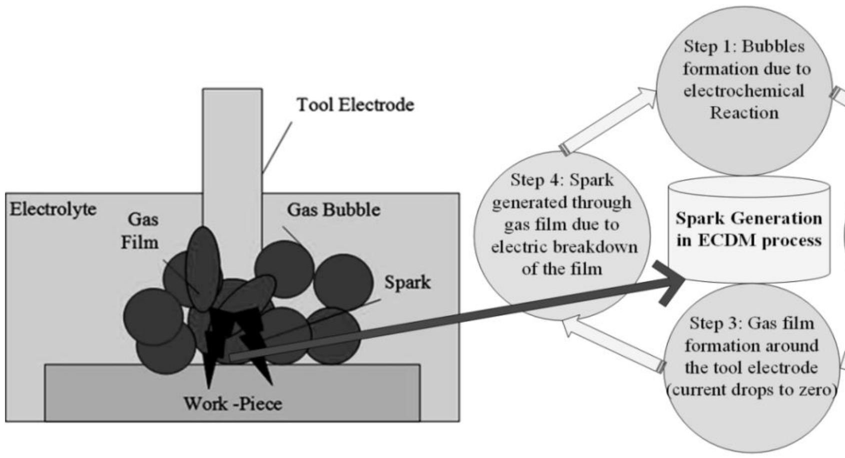

Fig. 3. a) Gas bubble formation and spark generation process, red and blue color represents Oxygen gas bubble and hydrogen gas bubble respectively, b) Step-wise spark generation mechanism in ECDM Process

This raises the temperature of the workpiece to a very high magnitude sufficient for its melting which resulted in a material removal due to thermal erosion followed by chemical etching action (De Silva et al., 1995; Jawalkar et al., 2012; Zhiyuan et al., 2018). Despite this, the explicit material removal mechanism has not been enacted completely. Various theoretical and experimental investigations have been done verifying that melting of the work piece (due to local heating) is the prime reason responsible for material removal (De Silva et al., 1995; Zhiyuan et al., 2018; Jain et al., 1999; Basak and Ghosh, 1997). Besides, several indications are there which reported in favor of chemical etching for material removal as well (De Silva et al., 1995; Fascio et al., 1999).

2.1 Spark Analysis

Spark generation mechanism in ECDM was demonstrated by explicitly Basak and Ghosh (1996, 1997) in which they proposed a critical voltage and critical current parameters required for machining and further announced that spark phenomenon is similar to a switching On/Off action of an electric switch. Jain et al. (1999) emphasized that each gas bubble acts as a valve that produces discharge in the form of an arc, once its breakdown occurs due to a high electric field. Wüthrich et al. (2005) mentioned that the immense current densities produced at the sharp edges of the tool resulting in spark initiation, requiring tool electrode (cathode) to be made of thin-section as compared to tool anode (auxiliary). Kulkarni et al. (2002) performed experiments for studying discharge mechanisms while machining different workpieces made of copper, tantalum, silicon, and brass. They used HCl as electrolyte with a concentration of 5wt% and applied a voltage of 155 V. They found similarity in the current behavior among all the workpiece materials with a difference in the magnitude of the peak values as monitored by resistive shunt method as shown in Figure 4. Crichton and Mcgeough (1985) evaluated the detailed mechanism of the spark with the application of pulsed voltage for the duration of 200μs.

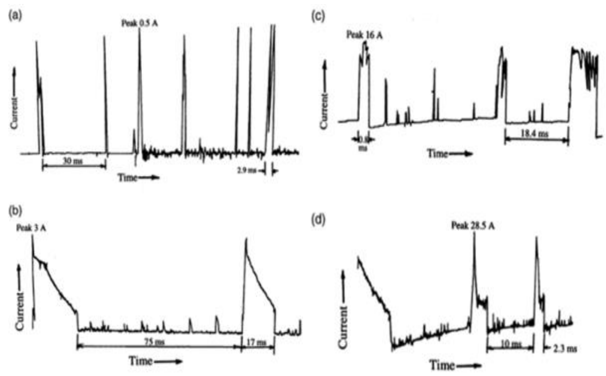

Fig. 4. Time varying current densities for: a) Silicon; b) Brass; c) Copper; d) Tantalum; Voltage (155V) at 5% wt/v HCl [46]

They demonstrated that spark generation across the electrolyte and tool electrode tip is a result of gas film formation of low ionic concentration around the electrode surface. Studies reported in the comprehension of the spark mechanism in ECDM (Pawar et al., 2018; Wei et al., 2011; Allagui and Wuthrich, 2009; Bhondwe et al., 2006; Bozkurt et al., 1996) are exhibited in Figure 5.

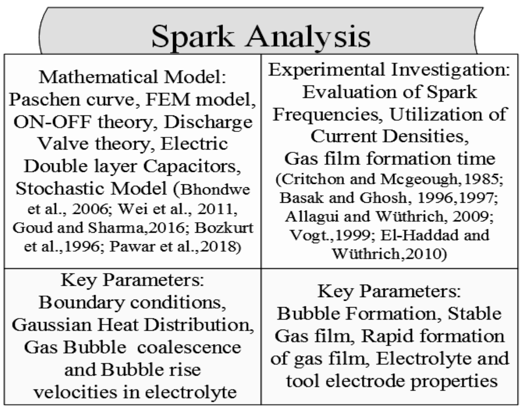

Fig. 5. Key parameters and studies reported in spark analysis

3. LITERATURE REVIEW OF EFFECTIVE PROCESS PARAMETERS

Various researchers have put forward their explanations based on laboratory experiments determining the performance of ECDM and the mechanism of material removal.

The influence of discrete process parameters (such as voltage, type of electrolyte and its concentration, tool electrode parameters like shape, size, and material, etc.) on response parameters such as removal rate of material, tool wear rate (TWR), surface finish (SF), over-cut, HAZ, etc. This section discusses some of the results of critical research in the ECDM process, highlighting the influence of the process parameters on the processing performance. The gas film is considered as the utmost parameter in determining the machining characteristics in ECDM. Fascio et al. (2003) examined the changes in gas film structure with rising voltage and divides the typical current-voltage characteristics of ECDM into five regions as shown in Figure 6. R. El-Haddad and Wüthrich (2010) have presented a successful model for predicting current-voltage characteristics required for stable gas film formation by incorporating gas film dynamics.

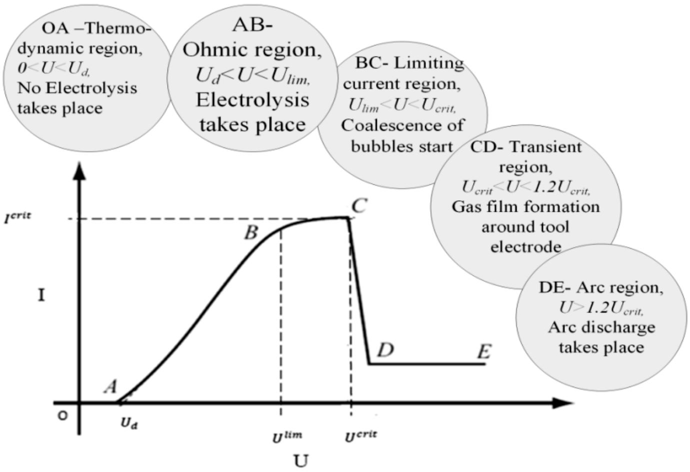

Fig. 6. Typical I-U characteristics of ECDM with five different regions, where I is mean current, I^{crit} is critical current density, U is applied voltage, U^{lim} is limiting voltage, U^{crit} is critical voltage and U_d is water decomposition [21]

Vogt (1999) explained the phenomenon of the gas film based upon wettability and proposed that the change in the wettability produces the gas film formation. It was concluded that electrode material and concentration of the electrolyte at the tool electrode vicinity are the main reasons responsible for the change in wettability. Wüthrich and Fascio (2005) evaluated that an increase in electrolyte temperature and applied DC voltage increases the removal rate of the material and the rate of tool wear during machining of glass using ECDM.

Other authors reported similar findings on applied voltage effect on MRR (Ladeesh and Manu, 2018; Chaubey and Jain, 2018; Unune and Mali, 2018). McGeough et al. (1983, 1984) concluded that applied voltage and feed rates are the most influential parameters in determining MRR as its rate increases at higher voltage and feed rate. Similar results were given by Harugade et al. (2013) as shown in Figure 7(a). Cao et al. (2009) reported that an increase in applied voltage will increase MRR along with the depth of machining (up to 55 μm). As the applied voltage increases further, they observed thermal damage and micro-cracks at the machining surface because of the inconsistent flow of discharge energies as shown in Figure 7(b). They also used a sensitive load cell to identify a contact across the tool electrode and workpiece which further produces a potential difference as a tool makes physical contact with the workpiece. Load cell proves very effective for maintaining a constant gap across the tool electrode and workpiece which enhances the flow of electrolyte and discharge energies, thereby giving better machining characteristics.

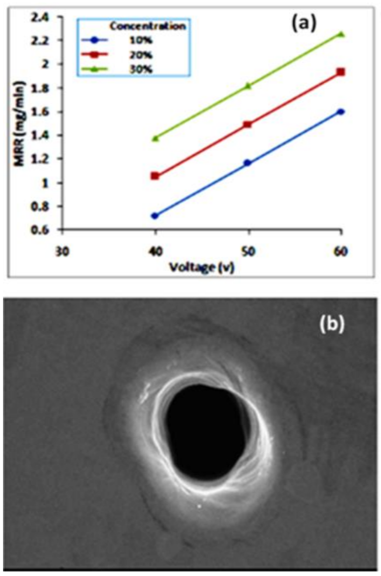

Fig. 7. a) Effect of voltage on MMR at different electrolyte concentration [32], b) Thermal cracks at hole entrance, 35 V [11]

Jawalkar et al. (2012) performed experiments to investigate the effect of influential control parameters on machining characteristics along with their contributions in ECDM machining of glass with stainless tool electrode. It was revealed that applied voltage shared the highest percentage of contribution (85.58%) in the removal of material, followed by the concentration of electrolyte (7.7%) and then feed rate (6.7%). Tandon et al. (1990) evaluated the effect of electrolyte conductivity and voltage on MRR and TWR in which they concluded that both MRR and TWR increase with the increase in electrolyte conductivity and applied voltage. Chak and Rao (2007) observed an increment in the conductivity of the electrolyte from 275 to 375mS/cm with an increase in its concentration (NaOH and KOH) from 5.5wt% to 15wt%, which further results into the enhancement of chemical action. Further, West and Jadhav (2007) performed micro-machining on borosilicate glass with different concentrations of electrolyte and its temperature as control parameters. Results showed that they successfully fabricated a spherical shaped microstructure at lower concentration values of electrolyte and its higher temperature. Similar findings were given by (Raghuram et al., 1995; Sankar et al., 2014; Tam et al., 1989; Malik and Manna, 2016; Rajput et al., 2019) on electrolyte parameters.

Yang et al. (2010) used three different tools (tungsten carbide, stainless steel, and tungsten), all fabricated by utilizing the wire electrical discharge grinding (WEDG) process to comprehend the wettability properties of different tool electrode materials. They reported that the wettability of the tool electrode materials affects the formation of gas film and its stability necessary for effective machining characteristics and its speed. Bhattacharyya et al. (1999) performed experiments for analyzing the predominant influential parameters on machining characteristics and to explore different geometrical tool shapes for better accuracy. They observed that tool electrode with a front tooltip and tapered sidewall is the most adequate tools for fabricating circular holes. Similar studies were reported on tool geometries. (Han et al., 2009; Yang et al., 2011; Jalali et al., 2009; Wüthrich et al., 2006; Tsui et al., 2008, Behroozfar and Razfar, 2016; Ladeesh and Manu, 2018). Gautam and Jain (1998) have concluded that high-speed tool rotation will deteriorate machining features while analyzing the process capabilities of ECDM using tool kinematics. Ziki and Wüthrich (2011) emphasized that the stainless steel (SS) tool, when used with pulse voltage results in high machining accuracy and less tool wear (see Figure 8) because of its higher thermal conductivity and thermal expansion.

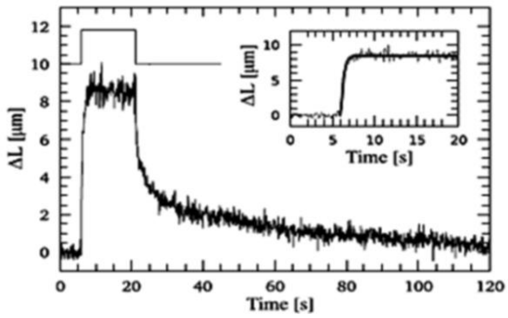

Fig. 8. Change in tool length (ΔL in μm) as a function of machine time (s), Workpiece- Al_2O_3 plate, Electrolyte- 30 wt. % NaOH [99]

Harugude et al. (2013) found that there was declination in MRR of soda-lime glass from 2.32 to 1.49 in mg/min as the distance across the tool electrode and workpiece (or IEG) increased from 20 to 40mm when machined at 60V with 30 % KOH as an electrolyte.

Yang et al. (2011) have investigated the effect of tool geometry on its wear rate and surface finish while using the tungsten carbide tool electrode with two different shapes as shown in Figure 9 (spherical end shape, diameter 150μm, and cylindrical shape, diameter 100μm). The results exhibited a decrease in tool wear and machining time with the utilization of a spherical shaped tool electrode.

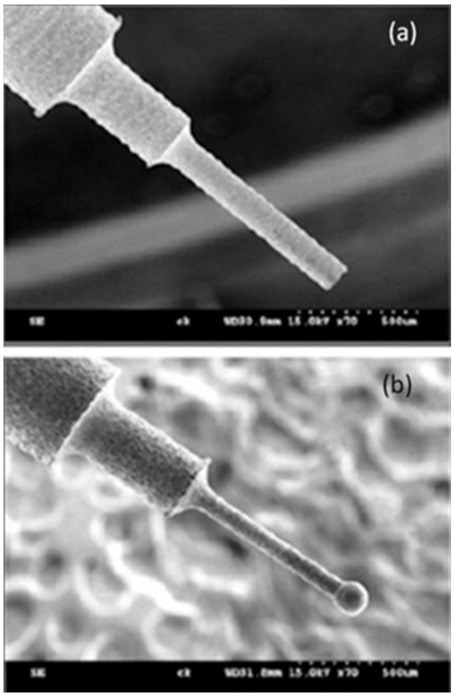

Fig. 9. SEM images of different tool shapes [92]

A summarized report on different process parameters is highlighted in Figure 10. Moreover, a critical study on the influence of different process parameters on MRR for different workpieces like Quartz (Laio et al., 2013; Nguyen et al., 2015; Hourng et al., 2014; Saranya et al., 2015; Goud and Sharma, 2017), Ceramics (Doloi et al., 1996, Singh et al., 1996; Sarkar et al., 2006), Composites (Nesarikar et al., 1994; Manna and Narang, 2012; Sarda et al., 2016), Glass (Wuthrich et al., 2005; Kumar and Dvivedi, 2018; Singh and Dvivedi, 2018, 2018a; Ho and Wu, 2018; Hajian et al., 2016; Cheng et al., 2010; Pankaj et al., 2016) at different machining conditions in ECDM is shown in Figure 11.

From the above literature, it is very much clear that process parameters significantly influenced the removal rate of the material, tool wear rate and other response parameters in ECDM.

4. OPTIMIZATION OF PARAMETERS

The selection of an optimum range of parameters is highly imperative for the better performance of ECDM. The approach adopted by the design of the experiment is found to be prevalent for solving optimization problems in engineering applications. ANOVA is one of the most progressive and popular techniques being used in process optimization. Besides, many studies were reported in the utilization of other successful optimization techniques such as S/N ratio, GRA (Grey relational Analysis), genetic algorithm, particle swarm optimization (PSO), ABC (artificial bee colony) algorithm, etc. (Goud and Sharma, 2017; Doloi et al., 1999; Singh et al.,1996; Samanta and Chakraborty, 2011; Karaboga and Akay, 2009; Shanmukhi et al., 2015; Feng and Hua, 2011; Kumar and Kumar, 2014; Adalarasan et al., 2014). So far many mathematical models were also built for predicting the optimum parameters in the ECDM process.

5. PILOT EXPERIMENTS

The pilot experiments were performed to investigate the influence of process parameters on machining characteristics during micro-drilling operation. The workpiece chosen for the study was soda-lime glass having 1mm thickness. The other machining parameters were selected based on a literature study and given in Table 1. Experiments were designed using one factor at a time (OFAT) technique in which one variable changes at a one time while keeping other parameters fixed during the study. The electrolytic cell was made up of non-toxic and non-reactive polycarbonate material in which the workpiece holding device was attached.

Table 1. Machining conditions used in Pilot study

Parameter	Value
Applied Voltage	40V-50V
Electrolyte	NaOH
Electrolyte Concentration	15 %-20% (%wt. /v.)
Electrolyte Temperature	50°C
Inter Electrode Gap	40 mm
Tool Immersion depth	1mm (Approx.)
Tool Material	Stainless Steel
Tool Shape	Cylindrical and Pointed
Tool Size (Φ)	500 μm
Machining time	3 Minutes
V=Volt, wt. /v. = Weight/Volume, °C= Degree Celsius, mm=Millimeter, Φ=Diameter, μm=Microns.	

A continuous DC voltage was applied between the electrodes for prompting electrochemical reactions. The rate of material removal or MRR was computed by measuring the work material mass before and after micro-drilling operation divided by the total machining time as given in equation (1).

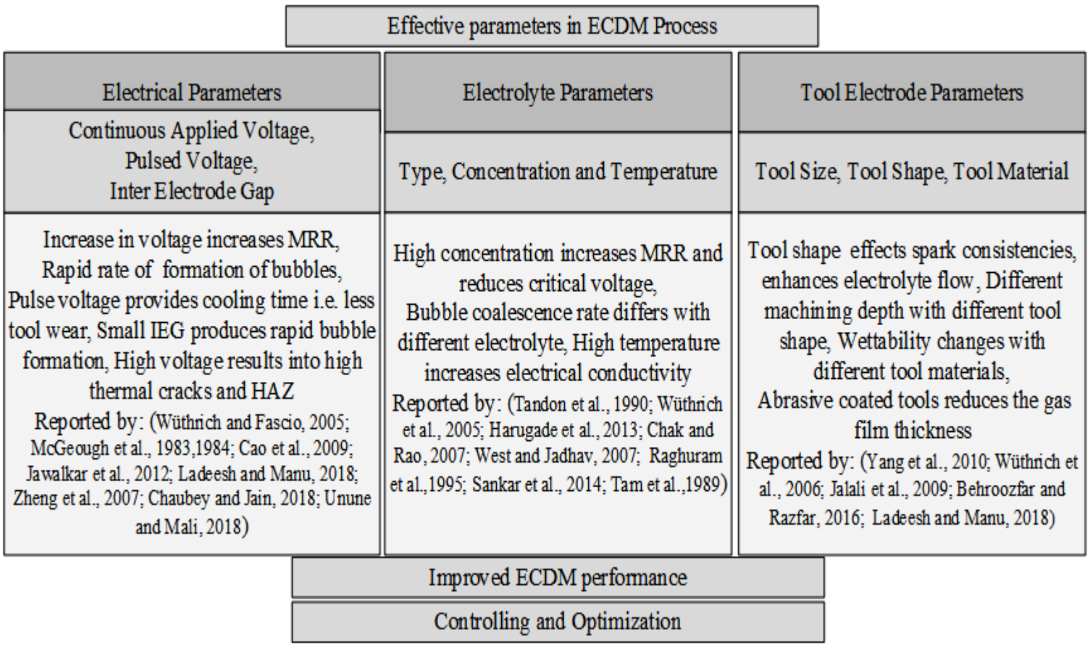

Fig. 10. Summarized report on effective process parameters in ECDM process

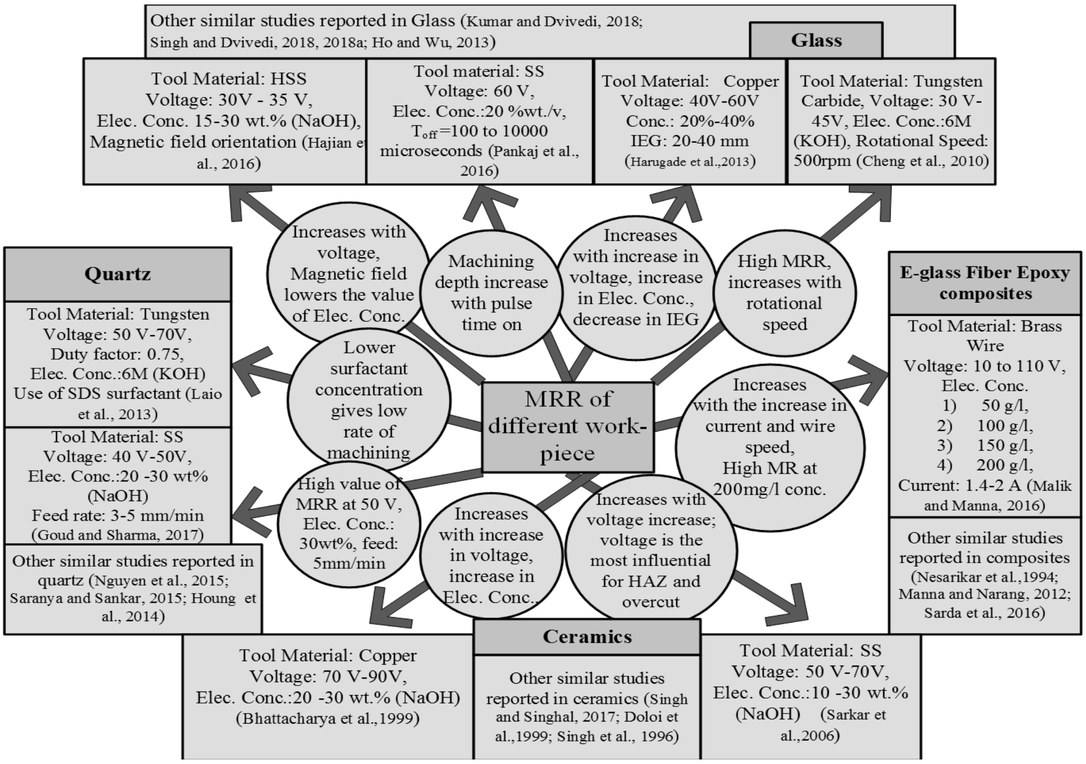

Fig. 11. Critical analysis for influence of different process parameters on MRR for different workpieces

$$MRR = \frac{m_1 - m_2}{t} \qquad (1)$$

where, m_1 - Mass of the soda-lime glass before machining; m_2 - Mass of the soda-lime glass after machining. A weighing machine of model CAS was used for measuring mass with a least count of 0.0001 g. The state of the machined hole was analyzed by using an inverted microscope for computing thermal cracks, HAZ and hole entrance diameter.

5.1 Case I

The Effect of applied voltage on MRR was investigated while keeping other parameters fixed. The applied voltage was increased from 40V to 50V at three different levels of viz. 40V, 45V, and 50V.

Result Analysis

It was seen that the removal rate of the work material increases with the increase in voltage due to the rapid generation of hydrogen bubbles, thereby resulted in a high intensity of spark over the work material. The plot of MRR with increasing Voltage is shown in Figure 12.

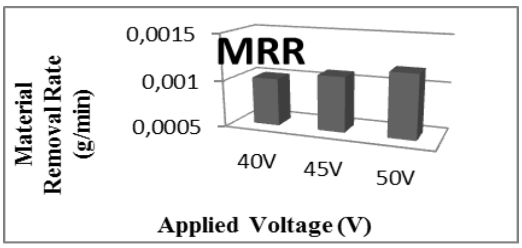

Fig. 12. Effect of voltage on MRR, 15 % wt/v NaOH, machining time: 3 min., pointed tool electrode

An increment of 8% and 17% was found when the voltage was increased from 40V to 45V and 40V to 50V respectively. Besides, a large number of thermal cracks and HAZ were also observed with the increase in applied voltage from 40V to 50V as shown in Figure 13.

5.2 Case II

Effect of electrolyte concentration on MRR and critical voltage was evaluated during micro-drilling operation. The concentration was increased from 15% to 20% by increasing the weight percentage of NaOH in aqueous solution.

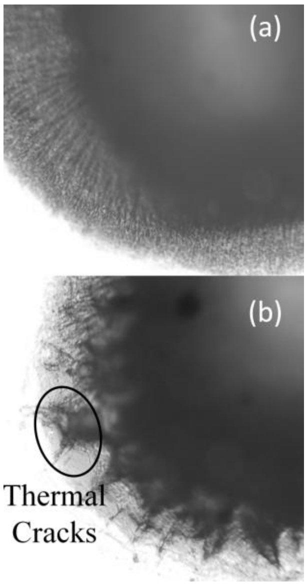

Fig. 13. Thermal Cracks at a) 40V; b) 50V, 15% wt. NaOH

Result Analysis

A decrease in the magnitude of critical voltage was observed from 33V to 28V due to the presence of more OH^- ions in the solution. The transportation of H^+ and OH^- ions enhanced in the presence of higher concentration electrolytes. The removal rate of the material also increases from 0.0031mg to 0.0033mg with the increase in electrolyte concentration due to the increased rate of ions dissolution, when machined at 40V for 3 minutes.

Few studies also reported that at higher electrolyte concentration, etching action increases further which results in high MRR. Thus, higher electrolyte concentration produces high MRR but the possibility of getting thermal cracks at the edges becomes prominent also as shown in Figure 14. It is suggested to machine work materials at lower applied when electrolyte concentration is high to prevent thermal damage to the work material.

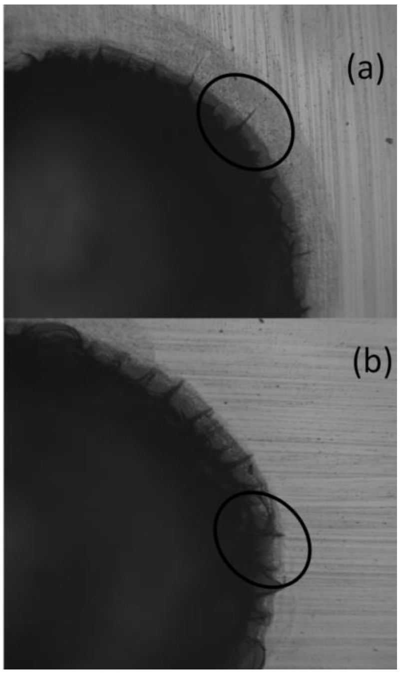

Fig. 14. Thermal cracks at (a) 15%, (b) 20% NaOH concentration, Machining Voltage: 40V

5.3 Case III

Effect of different tool electrode shape on MRR, machining time and hole entrance depth was evaluated. Two different tool electrodes were used for comparing the machining performance i.e., cylindrical tool electrode and pointed tool electrode. Machining time was evaluated for a constant machining depth of 1mm.

Result Analysis

The experimental result revealed that tool shape significantly affects the machining performance in terms of gas film stability and electrolyte flow. More MRR was found in a pointed tool electrode as compared to the cylindrical tool electrode as shown in Figure 15. An increase in material removal rate was explained due to more uniform spark consistencies in the pointed tool electrode when compared to the cylindrical tool electrode. Also, the pointed tool electrode enhances the flow of electrolyte at higher machining depth (i.e., hydrodynamic regime >300µm). The schematic diagram exhibiting the electrolyte flow in two different tool electrodes is shown in Figure 16.

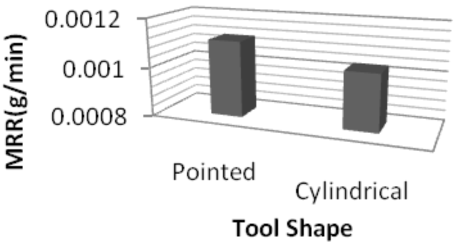

Fig. 15. Tool Electrode effect on Material Removal Rate (MRR), Machining voltage: 45V, 15%wt/v. NaOH, Machining time: 3min.

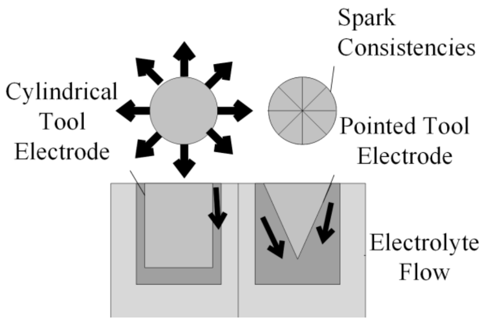

Fig. 16. Spark consistencies and Electrolyte flow in different tool shape [65]

The plot of machining time versus tool electrode shape is given in Figure 17. A decrease in machining time for machining 1mm deep micro-hole was found due to the enhanced electrolyte flow. A similar result (decreased hole entrance diameter) was observed in the case of hole entrance of the micro-hole due to uniform and channelized spark consistencies in the case of pointed tool electrode. On the other hand, cylindrical tool electrode produced a 'fringing effect' or crater formation at the bottom of the micro-hole due to the generation of sparks only at the circular rim as shown in Figure 18.

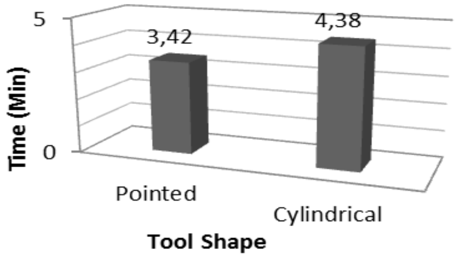

Fig. 17. Tool electrode shape effect on machining time for a constant machining depth (1mm), machining time: 45V, 15%wt/v. NaOH.

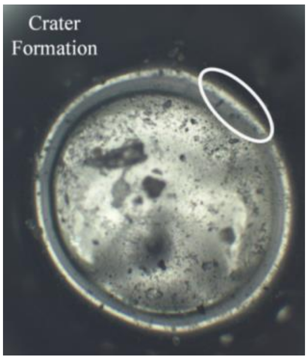

Fig. 18. Crater formation or fringing effect due to spark consistencies at the circular rim of the cylindrical tool electrode

6. FUTURE RESEARCH POSSIBILITIES

Since ECDM is an exceptionally promising technique for machining electrically non-conductive materials, but there are areas that are still unexplored such as gas film stability, effective MRR with better surface finish, preheating of electrolyte, the mixed concentration of different electrolytes, new workpiece materials, triplex hybridization, etc. The future research possibilities in ECDM and possible outcomes are shown in Figure 19.

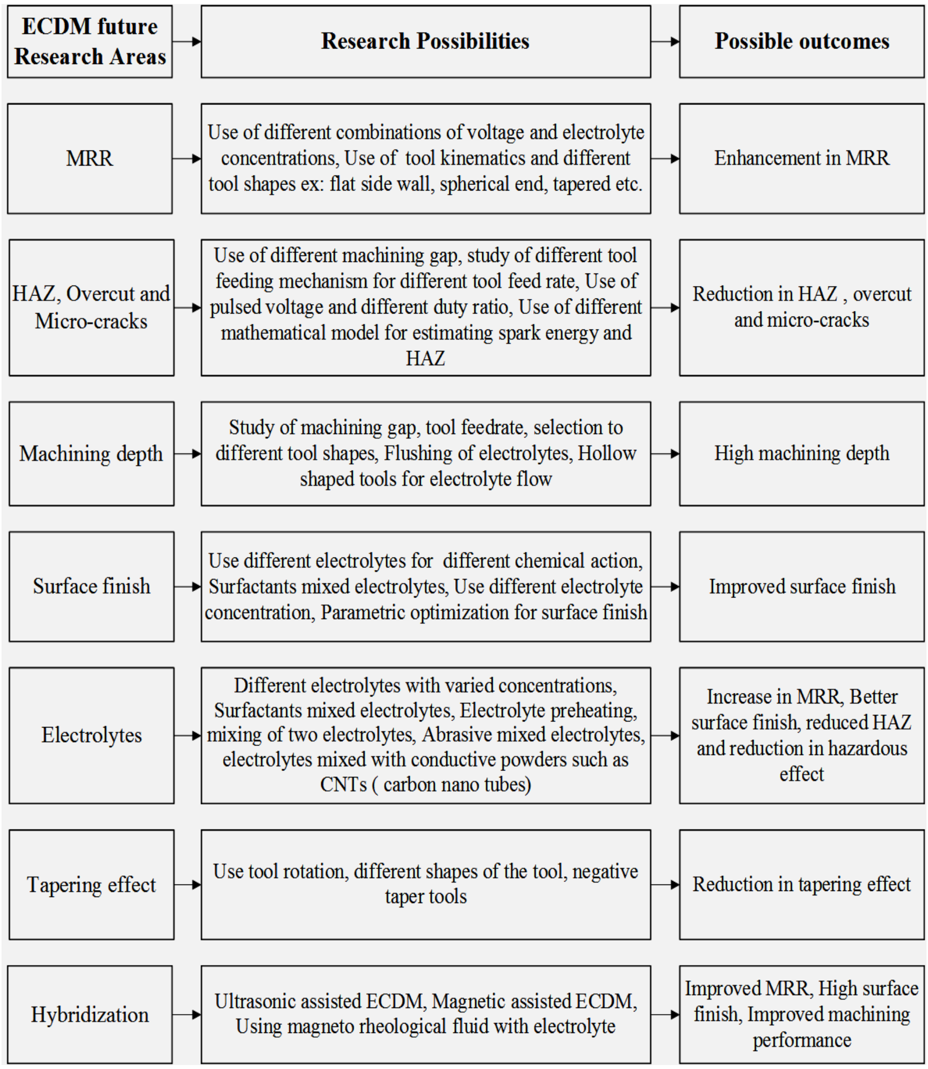

Fig. 19. Research possibilities in ECDM and their possible outcomes

7. CONCLUSIONS

ECDM is a very complex phenomenon involving several methodologies of material removal mechanism viz. thermal erosion, chemical etching, thermal spalling, etc. and its performance solely depends upon the selection of discrete process parameters. Based on literature review and pilot experiments, it is concluded that by selecting, controlling or optimizing the critical process parameters, an effective and repeatable machining can be achieved with high machining resolutions. Some of the important conclusions derived from this comprehensive review are as follows:

•ECDM process is proved to be an emerging tool for machining non-conducting engineering materials (quartz, glass, ceramics etc) with required accuracy and precision.

•Different experimental setup can be easily developed using cathode tool (conductive in nature), auxiliary anode and workpiece dipped in an aqueous solution of electrolyte (NaOH, KOH etc).

•Gas film stability and spark consistencies are the key determinant parameters for repeatable machining. Applied Voltage and electrolyte concentration are the most influential parameters for material removal rate. Pulse voltage helps in reducing the HAZ at the sharp edges if used within a limited range of ON/OFF ratio.

•Increase in electrolyte conductivity enhances the gas film stability at the vicinity of tool electrode which further increases material removal rate.

•Tool electrode shape significantly affects the machining characteristics in ECDM process. A better tool design with optimum shape such as spherical, helical, flat sidewall tool, tapered tool etc. can be used for reducing the taper phenomena and overcut of the micro-hole in ECDM.

•Tool wear can be reduced with optimum tool material selection and tool feed mechanism. It can be reduced further by using pulse voltage for constant machining time under given working conditions.

•Different experiments can be performed to study the influence of different tool geometries or tool motions on removal rate of material, HAZ and TWR.

8. ACKNOWLEDGEMENTS

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