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Micro-machining with ECDM: A state of art approach

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Abstract*— *Electro-chemical discharge machining (ECDM) is a proven and novel technology for machining electrically non-conductive materials such as glass, quartz etc with effective material removal rate (MRR). These materials are very difficult to machine with traditional machining methods owing to their brittle nature. Material removal mechanism in ECDM is a combination of both removal mechanism of both electro-chemical machining (ECM) and electro-discharge machining (EDM) simultaneously i.e. material removal occurs due to thermal erosion and chemical dissolution. This review article discusses the fundamental physical principle of ECDM process along with the reporting of the critical research findings on machining performance. The influence of various control parameters such as applied voltage, electrolyte concentration, tool shape, tool rotation and vibration on material removal rate, surface roughness and tool wear was discussed comprehensively. On the basis of literature study, it was observed that control parameters significantly influence the ECDM machining performance. The ECDM process can successfully machine electrically non-conductive materials with ease and highlights crucial reporting's of parameters which add to the existing literature.

Keywords*— *Spark, Etching, Electrochemical Discharge Machining, Electrolyte, Gas film.

I. INTRODUCTION

Non-conductive materials exhibit some numerous applications in micro-electrochemical systems (MEMS), micro-fluidic or lab-on-chip devices, because of their extreme peculiar properties like transparency, resistance to corrosion, resistance to high temperature and chemicals etc. These materials are very difficult to machine by traditional methods of machining. However, many non-traditional methods have been developed such as Diamond grinding, Ultrasonic Machining(USM), Abrasive Water jet machining (AWJM), laser beam machining (LBM), and ion beam machining (IBM) which can be successfully utilized for machining hard and brittle non-conductive materials. It was seen that these methods are equipped with various intrinsic limitations such as rough surface finish, high heat affected zone (HAZ). There are other efficient advanced non-traditional methods like electric discharge machining (EDM) and electrochemical machining (ECM) which can be utilized to machine only conductive materials. So in order to cope up the above mentioned challenges, a new effective and robust method has been developed for machining non-conducting and brittle materials. ECDM is recognized as a robust and hybrid machining process in which removal rate of material takes place by blending the removal mechanism of the principles of electric discharge machining and electro chemical machining.

II. ECDM WORKING OPERATION

ECDM is a machining process based on discharge phenomena in which the all tool electrode, auxiliary electrode and work material, together dipped in an aqueous solution of alkaline electrolyte like KOH or NaOH. The tool electrode is generally made as cathode while auxiliary electrode is made as anode and both are separated by a distance of few millimetres as shown in Figure 1. A potential difference (DC or pulsed voltage) is applied across the both electrodes in order to ignite the electrochemical reactions. A constant gap is maintained across the tool electrode- work material so that electrolyte flow remains active underneath the tool electrode. As soon as potential difference is applied, the electrolysis process starts taking place generally at lower voltage (20-30V) which results into the formation of tiny hydrogen bubbles at the interface of tool-electrode and oxygen bubbles at the auxiliary electrodes at the anode respectively. The intensity and formation of these tiny gas bubbles increases and their mean radius increases as the value of applied voltage increases due to the increase in the current densities. As a result, an insulating layer of gas bubbles are formed due to bubble coalescence around the tool-electrode which constricts the flow of current through the circuit in zero time. This gas film acts as a dielectric medium for the occurrence of spark once its electric breakdown occurs and the machining quality of the work material depends upon the quality of gas film. The gas film quality is influenced by several controlled parameters such as surface tension, buoyancy force, and thermo-capillary flow due to temperature gradient between tool and electrode and electrolyte, wettability, current density, resistivity of tool electrolyte, radius of the tool electrode and generates electric resistance to create high potential difference between the electrodes. The electrochemical reactions and cathode and anode are given below:

$$2H_2O + 2e^- \rightarrow 2(OH)^- + H_2 \text{ (on cathode)}$$
$$4(OH)^- \rightarrow 2H_2O + O_2 + 4e^- \text{ (on anode)}$$

As the applied voltage increases further, the work material temperature raises to a melting temperature which results into thermal erosion of the material due to vaporization and melting. The electrolyte etching actions also contributes to the removal action in ECDM process. When the potential difference becomes large enough for a given set of tool-electrolyte combination, electrical sparks occurs across the tool electrode and the electrolyte.

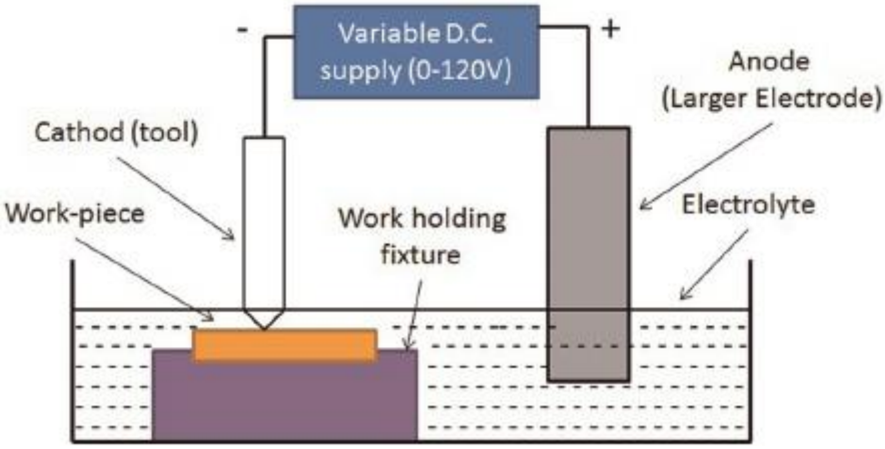


Figure 1 Schematic diagram of ECDM.

I. *Machining gap*

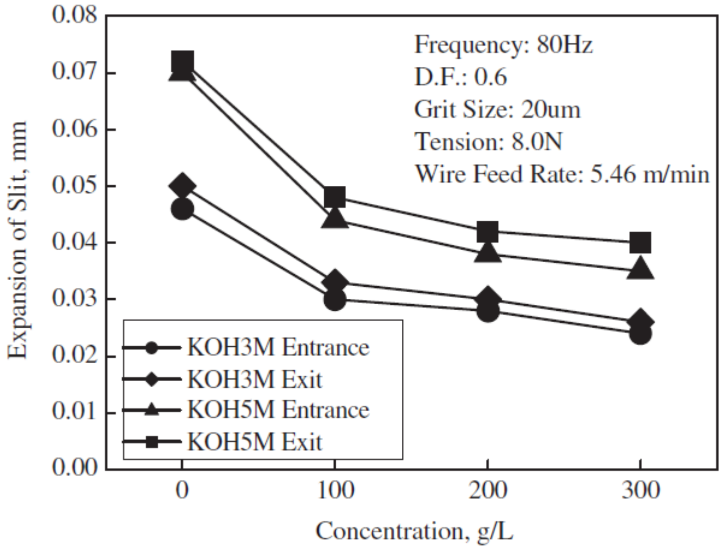
It was found that the machining gap is utmost crucial, as the tool comes in contact with the work material the rate of material removal and roughness changes abruptly due to non-availability of electrolyte underneath the tool electrode. If gap is crossed beyond a certain limit, then ECDM performance also deteriorates due to large dissipation of spark energy to the atmosphere.

II. *Tool feed*

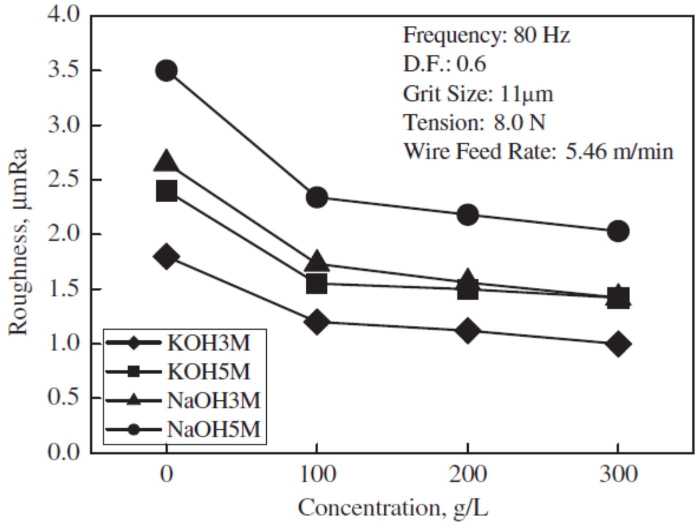
The feeding of tool electrode is also considered as one of the utmost crucial parameter determining the machining quality of the machined surface. If feed rate is higher than the removal rate of material then it results into the breakage of either work material or tool electrode. On the other hand, if feed rate is very low then it results into the increased time of machining as well as high heat affected Zone. Hence, overall machining gets affected. It can be done in three discrete ways and classified as given: (i) Gravity Feed; (ii) Constant Velocity Method; (iii) Closed loop tool feed. In gravity-feed mechanism, tool feed is achieved by the gravitational effect of the tool electrode or any other additional weight attached to it. This is one of the simplest and commonly used methods for machining non-conductive materials with ECDM process. It is preferred by many researchers and described as the effective method for fabricating micro-holes. However, mechanical contact across the tool electrode and work material sometimes results into the breakage of tool and work material. Also, more tool electrode wear occurs due to physical contact between them. The second method of tool electrode feed is constant velocity feed in which constant feed is applied to the tool-electrode. The feed is achieved by utilizing the stepper motor enabled drives. Thus, the selection of optimum tool electrode feed is very important for efficient and repeatable machining.

III. CRITICAL RESEARCH FINDINGS IN ECDM

Many researchers have put forward their studies regarding the ECDM performances during micro-machining of different non-conductive materials. Kurafuji and Suda K [1] were the first one who reported and clearly demonstrated the ECDM process during electrical discharge drilling. They emphasized the possibilities of drilling micro-holes in glass materials with effective material removal rate. Basak and Ghosh [2] have built a theoretical model for analyzing the material removal rate and compared the predicted results with the experimental one. On the basis of study, it was observed that a significant agreement was observed between the theoretically and experimental results. The similarity amongst these two confirms the validity of the developed model. The theoretical and experimental results illustrate an enormous increase in the removal rate due to the introduction of additional inductance. Liu et al. [3] successfully built up a grinding-aided ECDM process to enhance the machining performance of the process. A hard reinforcement phase of diamond particles were embedded on the tool electrode and removal rate of material is analyzed. The results showed that the addition of grinding action enhanced the removal rate *(three times*) and effectively reduced the formation of re-cast layer on the machined surface. Overall surface roughness (R_a) measured in this hybrid process was found to be reduced significantly. Yang et al. [4] utilized silicon carbide (SiC) abrasive particles to enhance the etching action and overall machining performance. Abrasives were added into the electrolyte during micro-cutting with wire electrochemical discharge process (WECDM). It was seen that overall roughness of the cut surface was enhanced substantially with the improvement of etching action. Moreover, improvement in reduction in the overcut and slit expansion was also achieved as shown in Figure 2. Gautam and Jain [5] added rotational effect to the tool electrode for enhancing the drilling depth of micro-holes. The machining was performed on electrically non-conducting ceramics, quartz and borosilicate glass. A significant improvement in the removal rate during micro-hole fabrication was achieved.



(a)



(b)

Fig. 2. (a) Slit Expansion variance at different concentration of abrasives; (b) Roughness variance at different concentration of abrasives (Yang et al. 2006).

Jawalkar et al. [6] performed experiments in order to study the effect of control parameters during micro-channelling on soda lime glass using ECDM process. Applied voltage and electrolyte concentrations were selected as input parameters while tool wear and material removal rate were chosen as response parameters. Results exhibited that applied voltage was the most influential parameter in controlling both Material removal and Tool Wear. Field emission scanning electron microscopy (FESEM) results confirmed the presence of micro-cracks on the surface of micro-channels. Chemical etching action was also found at the edges. Jain et al. [7] performed by providing rotational effect to the tool electrode eccentrically during micro-machining of quartz and alumina. The results revealed that after a certain value of electrolyte temperature, the ECDM process performance starts decaying. SEM images revealed that the combined action of melting and chemical etching provides effective material removal. Jawalkar et al. [8] performed the detailed parametric study of process parameters like applied voltage, electrolyte concentration and inter-electrode gap on removal rate using L9 orthogonal array. Two different electrolytes were used: NaOH and $NaNO_3$. Results exhibited that NaOH was more effective and efficient when compared to $NaNO_3$. Applied voltage was the most significant parameters with percentage contribution of 70.14%. Jain et al. [9] have performed electrochemical spark drilling with the utilization of abrasive cutting tools in order to improve the capabilities and potential of the process as shown in Figure 3. Alumina and borosilicate were chosen as a work-piece material. Increased material removal rate and drilling depth were obtained with abrasive cutting tools.

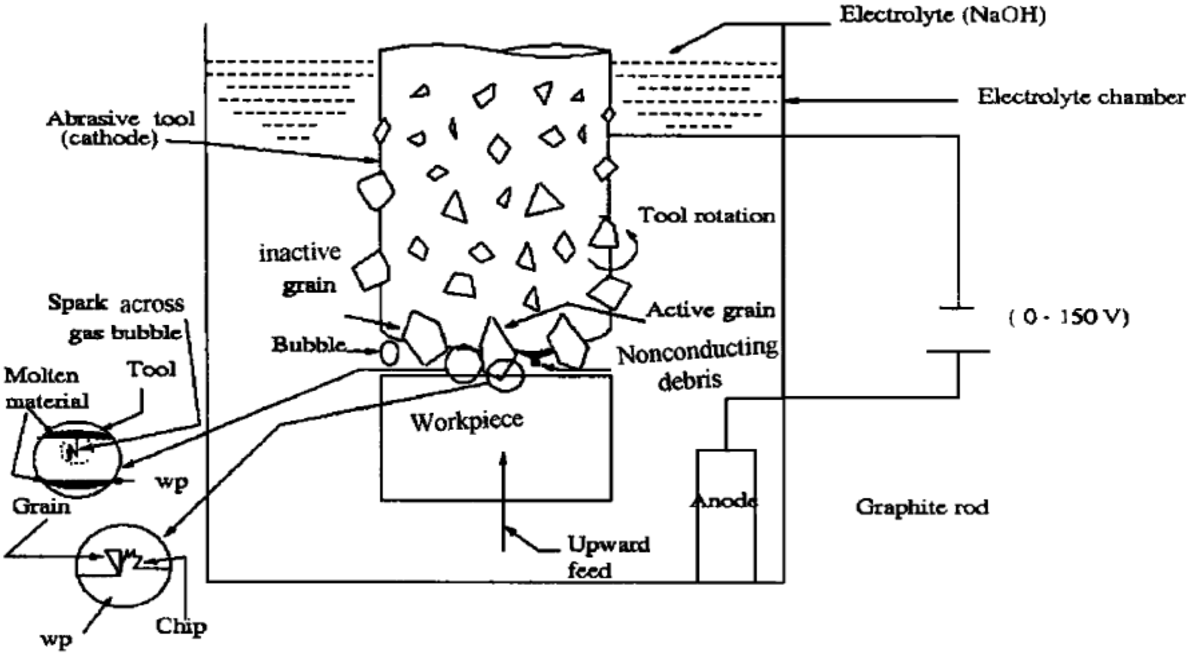


Fig. 3. Machining mechanism with abrasive cutting tools (Jain et al. 2002).

Cao et al. [10] utilized the application of load cell for detecting the mechanical contact across the tool electrode and work material in order to obtain a stable gas film at a lower voltage as shown in Figure 4. The immersion depth of the tool electrode inside the electrolyte was reduced as much as possible. As a result, high aspect ratio micro-structures were obtained at higher resolution in a glass work material. Utilization of pulsed voltage enhanced the surface quality and reduced the hole's size. Micro-holes having 60 µm diameter and a 150 µm depth was obtained with a 30 V pulse voltage. The KOH electrolyte results into a smaller machining gap when compared to NaOH.

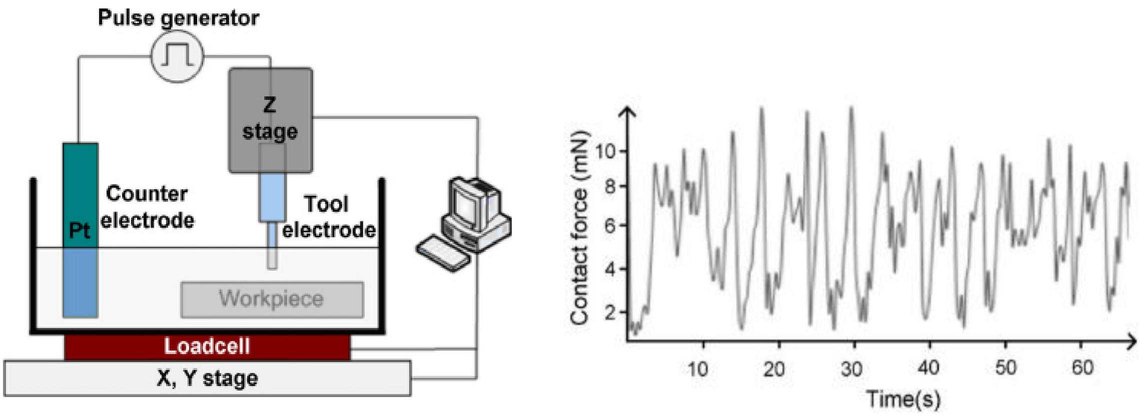


Fig. 3. (a) Schematic Diagram; (b) Load cell signal (Cao et al. 2009).

Jana et al. [11] has reported 'stick and jump' effect during machining of micro channels on glass. This happens generally due to higher application of tool feed rate in which the removal of work material ahead of the tool electrode does not get removed completely when compared to its sync with the tool advancement. The condition may also arise if the removed material gets re-deposited ahead of the tool electrode which subsequently escalates the work material to be removed during the motion of the tool as illustrated in Figure 4.

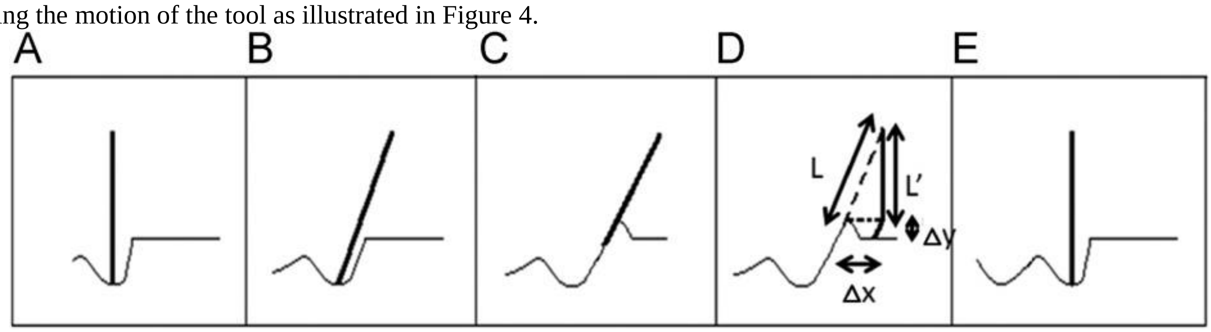


Fig. 4. Tool stick and Jump phenomena (Jana et al. 2012).

Harugade et al. [12] have performed experiments to identify the effect of electrolyte solution on material removal rate (MRR) on ECDM process when designed using standard orthogonal array (L9). The signal-to-noise (S/N) ratio is used to find the contributions of the control parameters, such as applied voltage, electrolyte concentration and inter-electrode gap. The Soda lime Glass is taken as work material while aqueous KOH and NaCl is used as electrolyte. Bhattacharyya et al. [13] investigated the effect of voltage and electrolyte concentration on material removal rate (MRR) and analyzed the phenomena of overcut in ECDM process during micro-machining of aluminium oxide ceramic work material using a pulsed dc voltage. The influence of the discrete effective tool tip shapes have also been studied and analysed as exhibited in Figure 5. The control parameters were taken as applied voltage (70 to 90 V), and electrolyte concentration (20 to 30%). NaOH was used as electrolyte with varying concentration. The results exhibited that MRR increases with increase in the applied voltage at different values of electrolyte concentrations. It was also found out that at higher voltages micro cracks and more HAZ were produced on the machined surface.

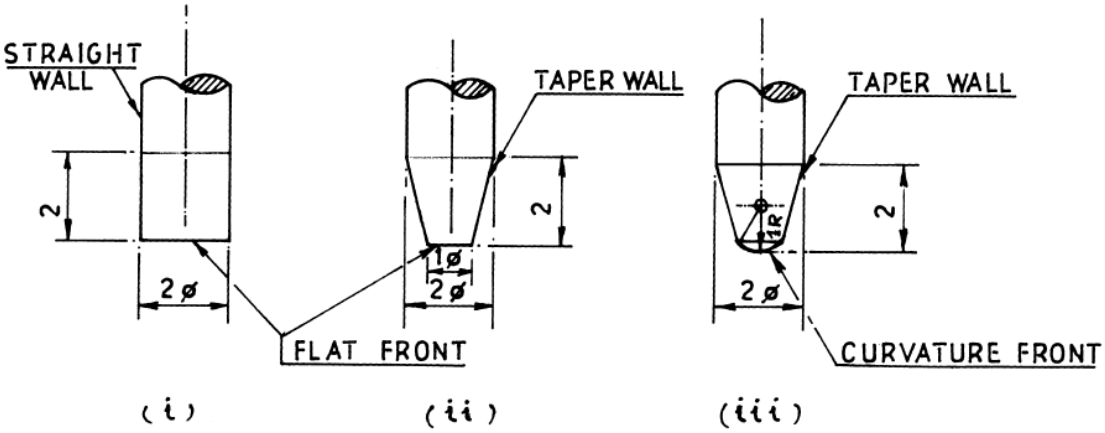


Fig. 5. Different tool shapes of the tip (Bhattacharya et al. 1999).

Skrabalak et al. [14] have successfully built up a mathematical model for estimating current values in ECDM process. They also made an attempt to develop an adapting fuzzy-logic controller for ECDM process. Xu et al. [15] performed analytical analysis to investigate the effect of magnetohydrodynamic (MHD) in the ECDM process using the high speed camera to track gas film formation with and without the magnetohydrodynamic effect. The results demonstrated that electrolyte circulation is enhanced and higher machining efficiency was also obtained. Moreover, gas film thickness also reduced which further results into the reduction of machined hole from 528 μm to 430 μm while the machining time was decreased from 50 s to 16 s. Paul and Hiremath [16] performed micromachining on borosilicate glass to investigate the effect of control parameters on Material Removal Rate (MRR) in ECDM. Optimum values of parameters were obtained using Taguchi method of optimization and computed as voltage of 60V, electrolyte concentration of 30 %wt and duty factor of 70%. Hiremath et al. [17] successfully machined micro-channels on quartz glass using micro ECDM having stainless steel (SS) tool of 370 μm diameter. Experiments were designed according to orthogonal array (L_9) at discrete levels of voltage (V), electrolyte concentration (wt %) and duty factor (%). Signal to Noise (S/N) ratio and Grey Relational Analysis (GRA) were utilized in order to optimize the process parameters for enhancing the ECDM performance. Optimum combination of parameters obtained through GRA was given as: 40 V, 20 wt% and 50 % resulted into enhanced MRR and reduced Tool wear rate. Rajput et al. [18] also instigated the influence of different tools shapes on MRR during micro-hole fabrication in ECDM process. Figure 6 illustrates the flow of electrolyte in different tool shapes. Soda lime glass was chosen as work material. It was found that spark consistencies improved with pointed end tool electrode when compared to cylindrical tool electrode. Enhanced flow of electrolyte was observed in pointed end tool electrode.

IV. FINITE ELEMENT STUDIES REPORTED IN ECDM

Several researchers have made an attempt to predict MRR under different machining conditions using Finite element analysis. Goud et al. [19] developed a three dimensional thermal model based upon FEM in order to predict MRR. The predicted results were compared with the existing experimental results and good agreement was observed between these two. Hardisty et al. [20] utilized Finite Element Method (FEM) to estimate the flux distributions in the electrolyte. The developed algorithms shows the possibilities of automatically change into the FE mesh in order to simulate the moving boundaries for tool movement over the work material. Panda and Yadava [21] also developed a 3-D transient model based upon finite element to predict the temperature distributions inside the work material which were post processed to estimate material removal rate (MRR). Gaussian distributed input heat flux was assumed in a spark region during Travelling wire electrochemical spark machining (TW-ECSM). The predicted results were compared with experimental results and a good agreement was observed amongst these two. Sathisha et al. [22] built up empirical models for analyzing ECDM process. In order to predict MRR, Regression Analysis (RA) and the Artificial Neural Network (ANN) was used and predicted results exhibited good agreement with the experiments results. ANN prediction of MRR was found better than regression model. ANOVA was used to find the percentage contribution of the process parameters in the ECDM process. The percentage of contribution of the electrolyte concentration was computed higher when compared to other parameters.

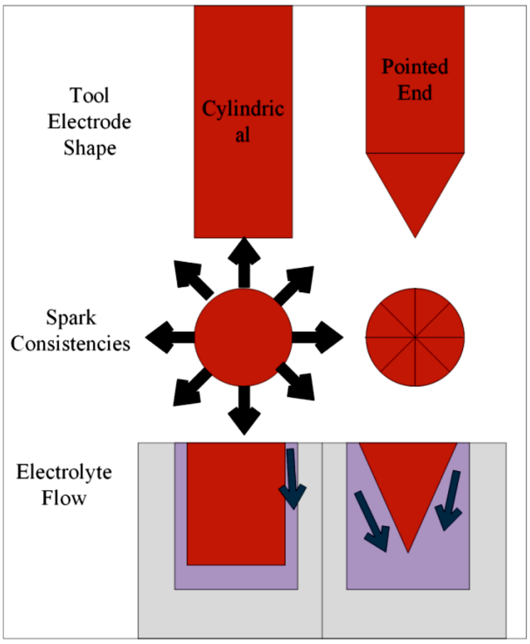


Fig.6. Flow of electrolytes and Spark consistencies in different shapes of tool (Rajput et al. 2019).

V. CONCLUSIONS

The present review article discussed the various reporting's of several authors on discrete control parameters during micro-machining with ECDM process. The major conclusions drawn from the review study are given below:

- ECDM exhibits a potential to machine electrically non-conductive materials with preferable machining rate.
- Applied voltage found to be most significant parameters for maximizing MRR with higher percentage contribution when compared to electrolyte concentrations and inter electrode gap.
- Tool rotational and vibration effect can significantly enhance the material removal rate due to enhance electrolyte circulation.
- Addition of abrasive particles results into the enhanced surface finish due to increase in abrasion action.
- Tool shape substantially controls the formation of gas film thereby resulting into uniform spark distribution over the work material.
- ECDM performance can be enhanced by its hybridization using magnetic fields, abrasive particles and various tool kinematics.

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