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Experimental investigation to improve the removal rate of material in ECDM process by utilizing different tool electrode shapes

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Abstract- The utilization of glass materials in MEMS application escalates over the past decades due to its peculiar properties which generates the need to produce micro-features on glass with supreme surface quality. ECDM has successfully evinced the micro-machining of glass material in which removal rate takes place through thermal erosion that includes local joule heating of the glass work material followed by chemical etching action. Besides, numerous intrinsic difficulties are there that required to be engulfed during micro-hole drilling process such as low material removal rate at higher machining depth (due to non-availability of electrolyte in hydrodynamic regime) and poor machining repeatability. This present study investigates the machining performance of ECDM process by using different shapes of the tool electrode i.e., pointed and cylindrical tool in order to improve the material removal rate. Experiments were performed according to taguchi's L9 orthogonal array and response measurements (Material Removal Rate or MRR) were analyzed through S/N ratio to identify the optimum range of process parameters. Results exhibited that pointed tool produces more uniform spark consistencies and also enhances the flow of electrolyte; thereby results into high material removal rate due rapid gas film formation. Pointed tool demonstrates the improvement in MRR with applied voltage being the most dominant parameter(64.83%) followed by electrolyte concentration(22.17%) and Inter-electrode gap (3.30%) at higher level of all three parameters (Optimum : A3B3C3). On the basis of experimental investigation, micro-holes were successfully drilled on glass material with improved material removal rate.
Keywords: Material Removal rate, Gravity feed, micro-holes, ECDM, S/N ratio

I. INTRODUCTION

With the increased applications of glass material in the field of MEMS (Micro-Electro-Mechanical System) like micro-needles, micro-pumps etc, there have been an escalation in the process of product miniaturization which further prompts the development of more effective and prominent machining processes with consistent repeatability. Glass exhibits one of the most prudent properties in terms of its high resistance to chemical resistance, low electrical conductivity and transparency that are considered as utmost indispensable properties for MEMS applications [1]. Electrochemical discharge machining (ECDM) is a unique non-conventional process for machining or processing non-conductive materials such as glass, quartz, and ceramics etc. by blending the machining features of both electrodischarge machining (EDM) and electrochemical machining (ECM). It comprises two electrodes i.e., tool electrode as a cathode and auxiliary electrode as an anode along with the work material; all immersed inside an alkaline based electrolyte as shown in Figure 1. A potential difference is implied between the cathode and anode (separated by a distance of few centimeters) in the wave form of Direct Current (DC) continuous voltage. Voltage application across the electrodes triggers electrochemical reactions which prompt the formation of tiny hydrogen gas bubbles at the cathode and tiny oxygen gas bubbles at the anode respectively. As applied voltage increases further, the density of hydrogen gas bubbles also increases which start amalgamating with each other to form a big size bubbles at the tool electrode vicinity. This results into the building up of a gas film (or insulating film) which constricts the flow of current across tool-electrolyte interface and spark produces due to electric breakdown of the gas film. Thereafter, work material is positioned just underneath the tool electrode by means of controller (or guide ways) at a small distance (*known as Inter Electrode Gap*) and removal of work material takes place due to thermal melting (EDM) and chemical etching action (ECM).
The first demonstration of ECDM was given by Kurafuji and Suda [2] in 1968 during micro-hole drilling of glass using electric discharge phenomena and successfully demonstrated that non-conductive materials can be machined using this process. ECDM spark generation mechanism was briefly demonstrated by Basak and Ghosh [3, 4] in which they proposed that there is requirement of critical current and voltage for initiating the ECDM machining process and described that spark mechanism is analogous to a switching On/Off action of an electric switch. El-Haddad et al. [5] built a stochastic model for predicting current and voltage values required for establishing a stable gas film formation by applying the fundamental principle of gas film dynamics.
Few researchers [6-8] also simulated the single spark in ECDM based upon Finite element methods to describe the heat transfer across the work-piece and predict the removal rate of the material. Experiments were also performed to correlate the

results with predicted value and results revealed a good agreement between them. Wuthrich et al. [9] successfully fabricated micro-holes in non-conductive materials and observed that stabilized gas film plays a significant role in determining the machining repeatability. ECDM proved very successful for machining glass material with required machining features [10-13]. Lim et al. [14] observed a taper phenomenon in a constant tool feed process during micro-hole drilling due to prolonged exposure of undesirable sparks at the hole entrance. Wuthrich et al. [15] successfully utilized the application of gravity assisted tool feed and concluded that flow of electrolyte plays a prominent role in determining machining depth. It was also observed that electrolyte flow is strenuous to attain at higher machining depth. In ECDM drilling process, two different regimes were classified on the basis of drilling depth (i) discharge regime (depth < 300 μm) where electric discharges dominants the machining and (ii) hydrodynamic regime (depth >300 μm) [16] where removal of material significantly rely upon electrolyte availability. Thus, machining rate at higher depths is low in hydrodynamic regime due to electrolyte deficiency which can be further enhanced by improving the electrolyte flow. Moreover, different tool electrode shape substantially influences the machining efficacy and its depth in micro-drilling operations owing to variable spark consistencies at the tool electrode surface thereby produces variable machining quality [17-19]. Various studies were reported in the utilization of ultrasonic vibrations and rotations to the tool electrode for improving the machining performance and reported significant results in terms of removal rate of work material, surface finish and tool wear rate [19-22]. Zheng et al. [23] successfully applied flat sidewalls tool electrodes in order to diminish the taper phenomenon occurred due to discharge from the sides of the tool. Wuthrich et al. [16] exhibited the improved spark consistencies with needle-shaped tool electrode in which sparks concentrated only at the tool-electrode tip. Yang et al. [24] evaluated the comparison of cylindrical shaped tool electrode and spherical end shaped tool electrode by measuring the machining performance and shape quality. It was concluded that spherical tool electrode enhances the machining performance owing to more stable discharge phenomena and improved electrolyte flow when compared to cylindrical tool electrode. From the literature, it is evident that many investigations have been done on glass work material using ECDM with different tools for producing micro-holes but attaining high removal rate of material and high depth micro-holes at a faster machining rate is still a strenuous task to be figure out. Thus, more experimental investigations are needed for analyzing and improving the removal rate of glass material at higher depths. This paper evaluates the effect of two different shapes of tool electrode i.e., Pointed tool electrode and Cylindrial tool electrode on removal rate during the fabrication of micro-holes on glass.

II. Experimental setup

A. Experimental setup

The experiments were carried out on developed setup which was adapted to vertical milling machine (Figure 1). The tool electrode motion is deliberately controlled by machine Z axis hand wheel having a resolution of 0.05mm. The experimental cell or electrolytic cell was built up of polycarbonate material (*non-toxic and non- reactive*) and filled with desired level of electrolyte in order to maintain an effective tool immersion depth. Work material selected for the study is soda lime glass with 1 mm thickness. Both tool electrodes viz. Pointed and Cylindrical were made up of stainless steel material having a diameter of 0.5 mm are used for machining micro-holes. A full wave and continuous DC voltage was applied across the cathode and anode having a range from 0 to 100 V, 10A. Work-piece was fixed on non-reactive fixture inside the electrolytic cell and gravity assisted tool electrode feed was used.

B. Machining procedure and measurements

The experiments were carried out in order to evaluate the influence of different tool shapes on removal rate of the glass material. The experiments were designed according to Taguchi's L9 orthogonal array and material removal rate was computed after each run.

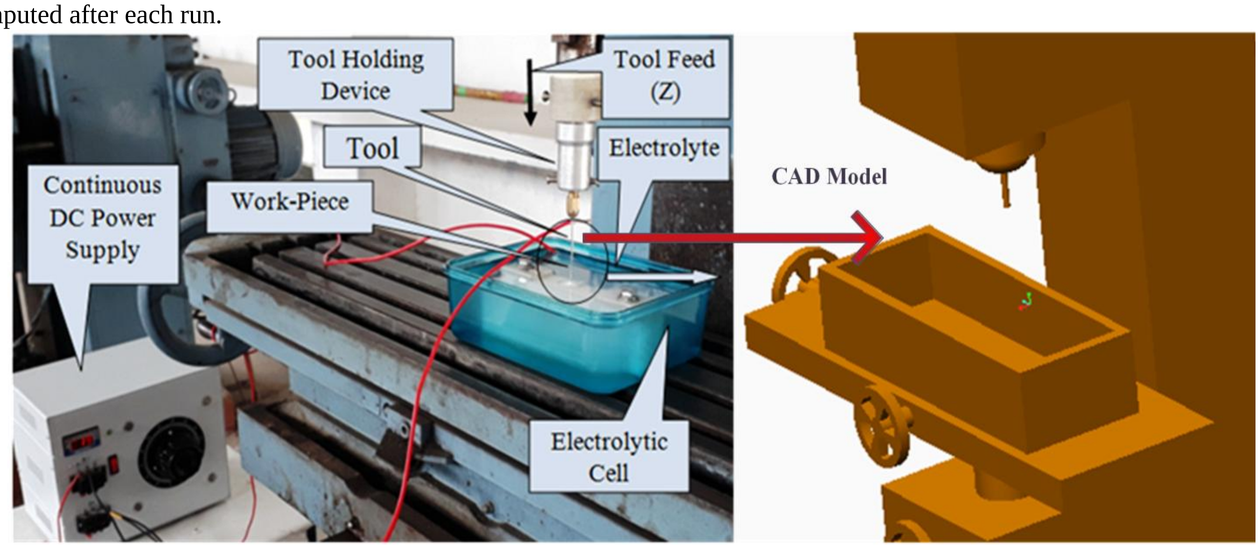

Fig.1 Developed Experimental Setup

Two different shapes of tool electrode was used for machining, i.e., Cylindrical and Pointed. An aqueous solution of NaOH was used as an electrolyte. Other details of machining conditions are highlighted in Table 1. Material removal rate (MRR) is computed by measuring the glass material weight difference before and after machining as given in equation, MRR=$(wt_1 - wt_2/t)$, where wt_1= glass material weight before machining (mg), wt_2 = glass material weight after machining and t= time in minutes. A weighing machine (model: CAY220, make: CAS corporation) having a resolution of 0.0001gm was used for measurement. An average of three measurements was taken. Initial machining was done in order to evaluate the process parameters effect on MRR. Initial process parameters used for machining were applied voltage: 45V, electrolyte concentration: 15% wt/v and inter electrode gap: 35mm. Selection of control parameters and their level for investigation were selected on the basis of literature survey, initial machining and experimental setup capabilities.

B. Optimization and ANOVA

The computed MRR was analyzed using Signal to Noise ration usually called as S/N ratio (larger the better) in order to attain the parameters optimum level for machining glass work materials as shown in equation 1. Moreover, significance level of process parameters and their contribution to the material removal rate was calculated through ANOVA [25-27]

$$S/N = -10\log_{10}[\frac{1}{n}\sum_{i=1}^{n} y_i^2] \qquad \text{Eqn. 1}$$

Where: y_i= response measurements in each experiment; n=number of measurements *(n=1* due to average value of MRR).

Table 1 Machining conditions used for micro-hole drilling

Constant Parameters		**Variable Parameters**				
		Levels		**I**	**II**	**III**
Cathode and Anode Material	Stainless steel	Applied Voltage (V)	**A**	40	45	50
Electrolyte	NaOH	Electrolyte Concentration (wt/v %)	**B**	15	20	25
Electrolyte temperature	50^{O}C	Inter Electrode Gap (IEG in mm)	**C**	30	35	40
Electrolyte Level	1 mm (approx.)	Machining time (Min)		2		

III. Results and discussion

A. S/N Ratio Analysis

The values of S/N ratio for MRR was computed on the basis of "larger the better" and mathematically calculated according to equation 1. Table 2 shows the response measurements and S/N ratios of MRR for both Cylindrical and Pointed tool electrode. Generally, higher magnitudes of S/N ratio corresponding to the certain combination of process parameters are taken as dominant parameters affecting the response measurements. In this investigation, delta value i.e., the difference between the highest and lowest mean S/N ratio was utilized to determine the parameters optimum combination. The delta values for three levels of parameters in pointed end tool electrode and cylindrical tool electrode is shown in Table 3 and 4, respectively.

From the delta values of pointed end tool electrode, it was observed that MRR significantly influenced by applied voltage (*highest: 8.876*), followed by electrolyte concentration (*5.027*) and Inter electrode Gap (lowest: *2.065*). The parameters are ranked also as shown in Table 4. Similar trend was observed in case of cylindrical tool electrode as parameters were influenced by applied voltage (*highest: 9.268*), followed by electrolyte concentration (*4.199*) and Inter electrode Gap (*lowest: 1.202*). Similar ranking was done for cylindrical tool electrode also. It was seen that for both tool electrode shape, the combination of optimum process parameters for maximum MRR value come out to be A3B3C3 i.e. *(50V, 25%, 40 mm)* as shown in Table 3 and 4; and main plot graphs (Figure 2). It was explained on the fact that at higher values of voltage and electrolyte concentration results into the increased intensities of hydrogen gas bubbles or rapid formation of gas film at the tool vicinity thereby enabling increased frequency of sparks and lastly, high inter-electrode gap enables the availability of more OH^- ions for etching action over the surface of work material.

Table 2 Taguchi's L9 Design and Response measurements of MRR for Pointed and Cylindrical tool

Experiments	Applied Voltage (V)	Electrolyte Concentration (wt/v. %)	Inter-Electrode Gap (mm)	Cylindrical Tool		Pointed End Tool	
				Average MRR (mg/min)	S/N Ratio MRR (dB)	Average MRR (mg/min)	S/N Ratio MRR (dB)
1	40	15	30	0.0352	-29.069	0.0394	-28.09
2	40	20	35	0.0427	-27.391	0.0449	-26.955
3	40	25	40	0.1150	-18.786	0.1171	-18.629
4	45	15	35	0.1061	-19.486	0.1089	-19.259
5	45	20	40	0.1009	-19.922	0.1019	-19.837
6	45	25	30	0.1699	-15.396	0.1739	-15.194

7	50	15	40	0.1401	-17.071	0.1429	-16.899
8	50	20	30	0.1795	-14.919	0.1819	-14.803
9	50	25	35	0.1688	-15.453	0.1709	-15.345

Table 3 Mean S/N ratio and Delta values for MMR in pointed end tool electrode

	MRR's mean S/N Ratio (Pointed End Tool Electrode)		
Level	Applied Voltage	Electrolyte Concentration	Inter Electrode Gap
1	-24.558	-21.416	-19.362
2	-18.097	-20.532	-20.52
3	-15.682	-16.389	-18.455
Delta	8.876	5.027	2.065
Rank	1	2	3

Table 4 Mean S/N ratio and Delta values for MMR in cylindrical tool electrode

	MRR's mean S/N Ratio (Cylindrical Tool Electrode)		
Level	Applied Voltage	Electrolyte Concentration	Inter Electrode Gap
1	-25.082	-21.875	-19.795
2	-18.268	-20.744	-20.777
3	-15.814	-16.545	-18.593
Delta	9.268	4.199	1.202
Rank	1	2	3

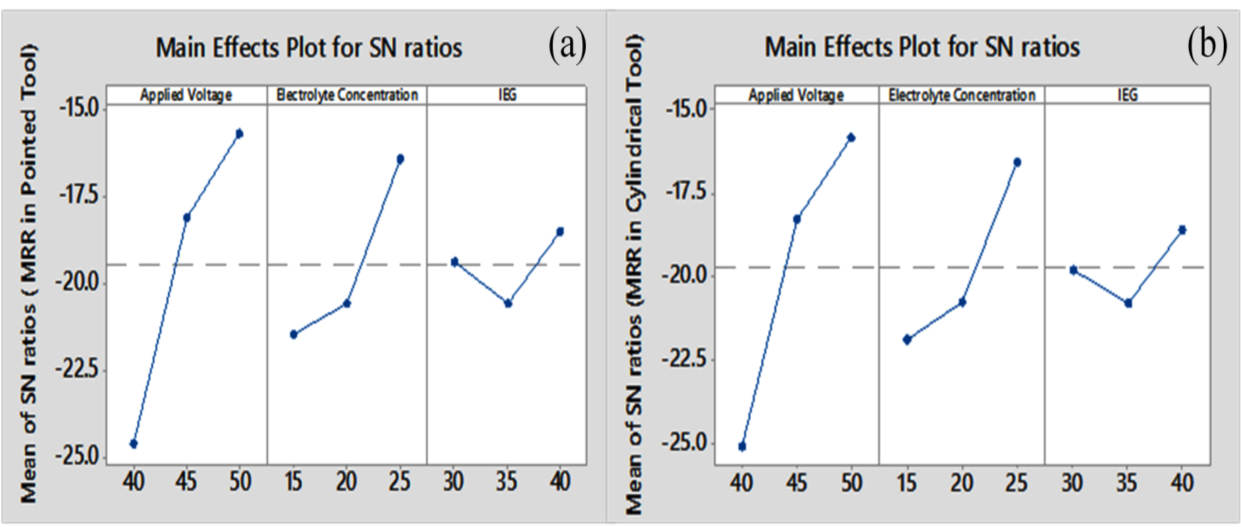

Fig.2. Plot for S/N Ratio (a) Pointed Tool (b) Cylindrical Tool

B. Effect of tool shape on Material Removal Rate

Tool shape substantially affects the removal rate in work material due to discrete way of spark consistencies and variable electrolyte flow as shown in Figure 3. It was notices that MRR is higher in case of pointed tool electrode when compared to cylindrical tool electrode as given in Table 2 owing to more spark consistencies.

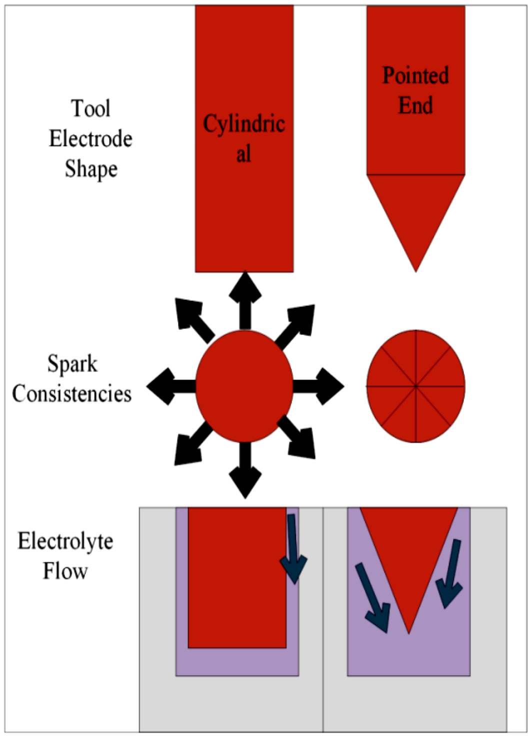

Fig. 3. Spark Consistencies and Electrolyte flow in different tool shape

Pointed tip tool electrode enhances the electrolyte flow because of reduced tool contact area with the work-piece at higher machining depth, in comparison to cylindrical tool electrode, which also contributed to the increase in MRR with improved drilling depth. The comparison of MRR at optimum level of parameters (*obtained from S/N ratio*) is shown in Figure 4.

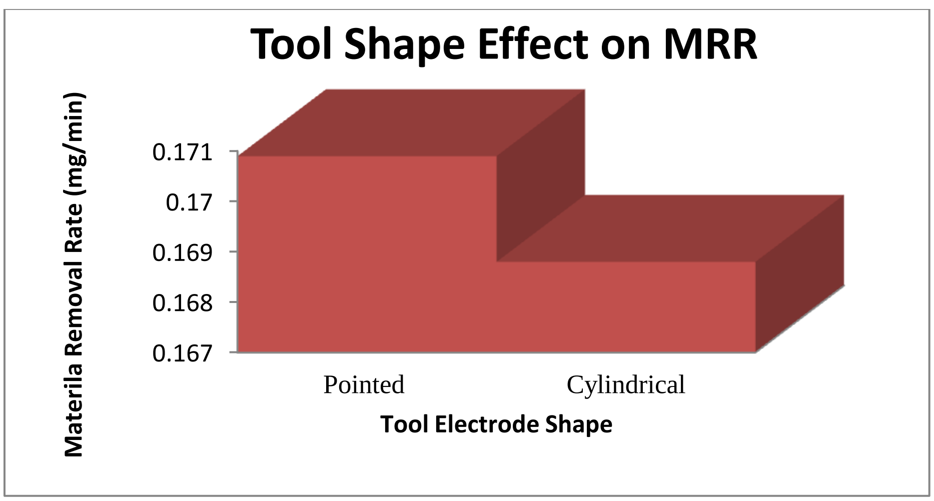

Fig. 4. Effect of tool shapes on MRR at Optimum parametric combination

C. Analysis of variance (ANOVA)

The foremost objective of ANOVA is to find the contribution of the process parameters on MRR and carried out on S/N ratio for both the tool electrode shape using MINITAB 18 software. The results for the ANOVA are shown in Table 5 for both pointed tool electrode and cylindrical tool electrode respectively. Results indicated that applied voltage is the most significant process parameter for controlling MRR in both the tool electrodes with a percentage contribution of 64.83% and 64.59% respectively, followed by electrolyte concentration (*22.17% & 22.09%*) and then Inter Electrode Gap (*3.30% & 3.35%*). The ANOVA results exhibits good agreement with delta ranking of S/N ratio as given in Table 3 and 4, respectively. The percentage contribution of process parameters in both tool electrode shapes are given in Figure 5.

Table 5 ANOVA results for Pointed and Cylindrical tool electrodes

Pointed Tool Electrode						
Source	**DF**	**Seq SS**	**Adj MS**	**F-Value**	**P-Value**	**Percentage Contribution**
Applied Voltage	2	126.35	63.178	6.68	0.130	64.83%
Electrolyte Concentration	2	43.208	21.604	2.28	0.304	22.17%
IEG	2	6.426	3.213	0.34	0.746	3.30%
Error	2	18.912	9.456			9.70%
Total	8	**194.902**				**100.00%**
Cylindrical Tool Electrode						
Source	**DF**	**Seq SS**	**Adj MS**	**F-Value**	**P-Value**	**Percentage Contribution**
Applied Voltage	2	138.341	69.170	6.48	0.134	64.59%
Electrolyte Concentration	2	47.324	23.662	2.22	0.311	22.09%
IEG	2	7.177	3.588	0.34	0.748	3.35%
Error	2	21.346	10.673			9.97%
Total	8	**214.187**				**100.00%**

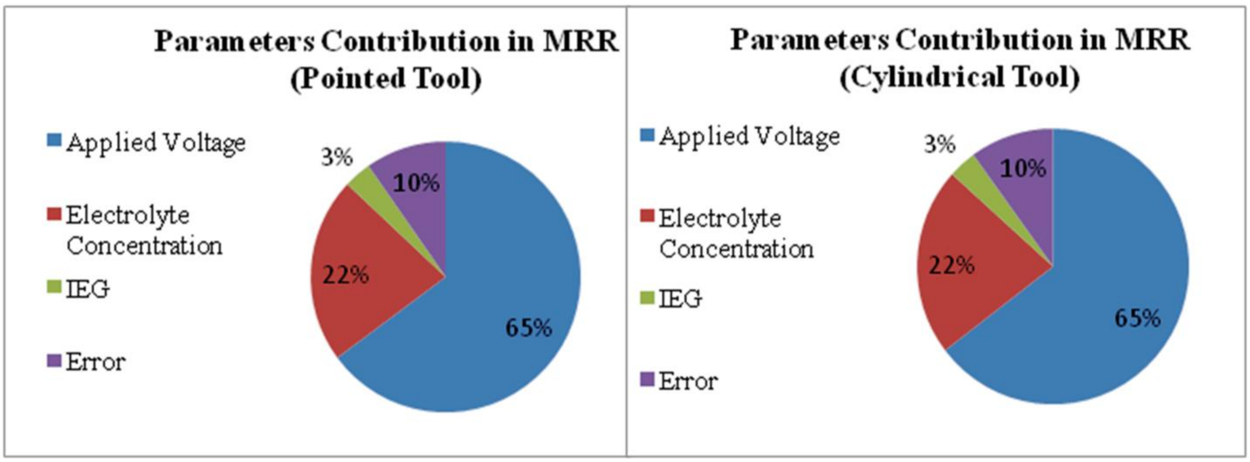

Fig. 5. Percentage contribution of Process parameters in MRR for Pointed and Cylindrical tool electrode

D. Effect of Parameters on Material Removal Rate

It was observed that applied voltage is the most significant process parameters in controlling the MRR, followed by electrolyte concentration and then Inter-electrode gap as illustrated in Table 5. It was also seen that with increasing voltage, the material removal rate also increases owing to the fact that more generation of hydrogen gas bubbles takes place which results into the formation of rapid gas film. Thus, spark intensities escalates with voltage increase, thereby resulted into High MRR as shown in Figure 6. Similar trend was observed in case of electrolyte concentration as it increases the material removal rate due to increase in electrical conductivity which results into high number hydrogen bubbles in the electrolyte. Also, number of OH^- ions in the electrolyte also increases which enhances the chemical etching action, thereby improved MRR. Effect of inter-electrode gap on MRR is shown in Figure 7 which highlights that any change in inter-electrode gap significantly affects the critical voltage and hence MRR.

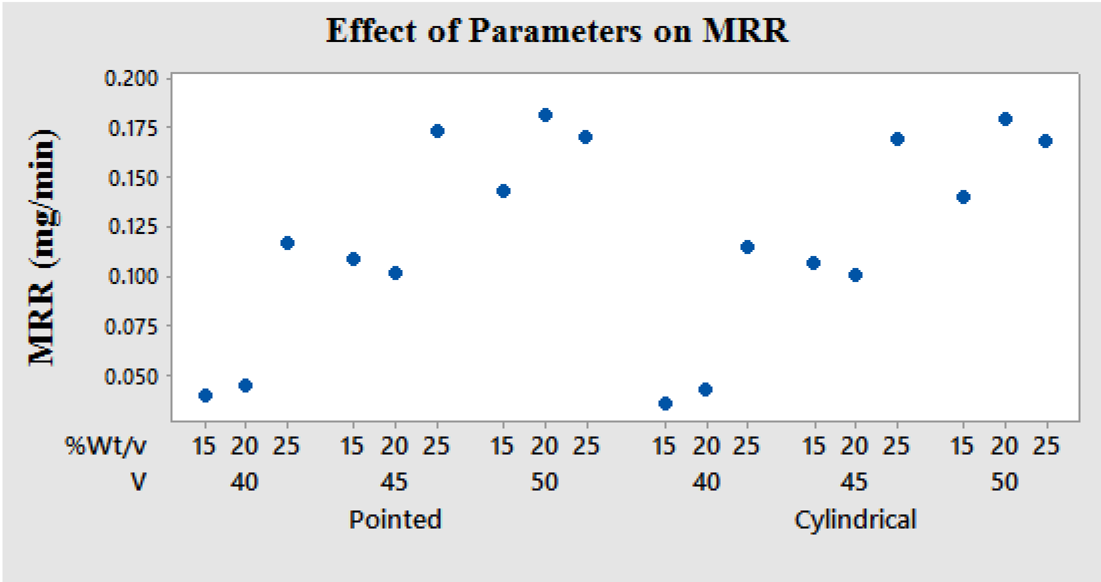

Fig.6. Effect of Voltage and Electrolyte Concentration on MRR

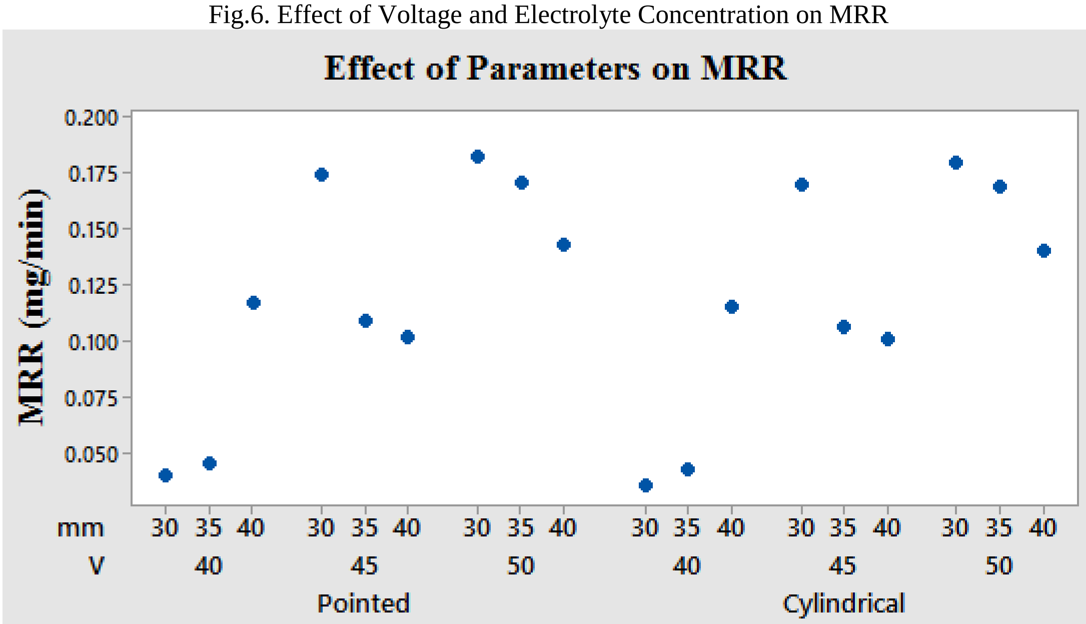

Fig.7 Effect of Voltage and IEG on MRR

IV. Conclusions

In the present investigation, the performance evaluation of ECDM process was done on Material removal rate by utilizing the Pointed and cylindrical tool electrode. Taguchi's L9 orthogonal array was used to analyze the machining performance along with S/N to determine the optimum range of process parameters. Applied voltage; Electrolyte concentration and Inter-electrode gap were the three process parameters used in the study. From the results, it was concluded that tool shape significantly effects the formation of gas film across the tool surface which further controls the spark concentration, thereby gives variable machining. The major conclusions drawn from the study are given underneath:

- Pointed tool gives maximum value of MRR (0.1819mg/min) due to more uniform spark concentration at the tool tip and more electrolyte flow. It prevents excessive spark concentration at the tool surface as in case of cylindrical tool electrode which results into "crater formation" at the hole's entrance.
- The optimum combination of process parameters for maximum MRR is A3B3C3 .i.e., (50V, 25%, 40mm), high level of all three process parameters for both the tool electrodes.
- Applied Voltage is the most dominant parameter for controlling the MRR in both the cases followed by electrolyte concentration and inter-electrode gap.

Future works can be extended for studying the different tool electrode parameters such as tool size, tool material and variable tool shape for improving the performance of ECDM process.

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