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Experimental Investigation of Micro-hole machining in Soda-lime glass through Electrochemical Discharge Machining For MEMS Applications

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Abstract

Electrochemical discharge machining (ECDM) is a non-conventional process that is primarily invented to the machine electrically non-conductive materials like quartz, ceramics, glass and the composites. The process has the capability to create the micro-channels, micro-holes and three-dimensional (3D) micro features, which currently, have been used in the microfluidic devices (Lab-on-chip) and Micro-electromechanical system (MEMS) packaging. The present study includes the analysis of effects of process parameters such as applied voltage, pulse frequency and duty ratio on the machining process. In the current analysis, a tapered stainless steel tool and aqueous NaOH electrolyte are used for the through hole machining. Top and bottom hole diameter is the primary focus in the analysis. To neglect the variability effects, three holes are machined at the same set of the condition and mean value is used in the study. Structural characterizations of drilled micro-holes are performed using optical microscopes and Scanning electron microscope (SEM).

Keywords: Electrochemical Discharge Machining, MEMS, Hole Diameter, Pulse frequency, Duty ratio, Scanning Electron Microscope

1. INTRODUCTION

The micro-electro-mechanical-system (MEMS) field has experienced an increased growth in recent years. Though Silicon is the most extensively used material, application of glass is also becomes important, especially in microfluidics and MEMS packaging. Glass is an important material used as substrate in MEMS applications as glass has the properties like low thermal and electrical conductivity, optical transparency, high hardness and biological compatibility etc. Due to the above mentioned advantage, glass substrates are used in Radio-frequency (RF) MEMS, microfluidics, Bio-MEMS and microsystems packaging [1, 2]. However fabrication of micro-features such as micro-channels and micro-holes in glass is a challenging task. Conventional machining techniques such as mechanical drilling have difficulties in machining the glass, especially in micromachining domain. Non-conventional machining techniques such as abrasive jet machining, laser machining, Ultrasonic machining and chemical etching can be used for machining the glass. But these processes have the limitations such as thermal cracks, large tool wear, low MRR poor accuracy and residual stresses etc. ECDM can be a good alternative which has the potential to create high aspect ratio micro holes, micro channels and complex features in glass and other non-conductive materials.

Pioneering work of Kurafuji and Suda introduced the process that made drilling of glass possible. [1]. All the other non-conducting difficult-to-machine material like Granite, Refractory, Aluminum, Plexiglas, Quartz etc. can also be machined through this process. Electrochemical discharge machining is a hybrid non-conventional machining process which combines the prominent effects of electrochemical machining and electric discharge machining. The basic idea behind ECDM was to use electrolyte as a conducting medium and generate sparks by increasing the voltage beyond a critical value which can then machine the non-conductive material by melting and evaporation followed by some amount of chemical etching [3]. The process is economical since, it requires minimum number of equipment's.

Singh et al. used ECDM for machining of piezoelectric ceramic material and investigated the effects of supply voltage and concentration of electrolyte on average diametral overcut and material removal rate [4]. Material removal rate (MRR) varies proportionately with supply voltage and electrolyte concentration gravity feed is utilized where feed is given to work-piece and tool electrode kept in constant position. Basak et al. [5] developed an analytical model for MRR of ECDM assuming cylindrical plasma channel and lifetime of single electrical discharge as 100 ms. They proposed the parameter 'inductance', which can lead to substantial increase in MRR. They discovered that an extreme amount of thermal spark energy (maximum spark intensity of 2000 J/cm^2) results in temperature rise on the work-piece surface and material removal due to melting and evaporation of the work-piece material. Bhattacharyya et al. [6] Conducted the experiments to determine the effect of electrolyte in the material removal of of aluminium oxide ceramic work-pieces at applied voltage (70 to 90 V).$NaNO_3$ was tried initially but due to electrochemical reactions, chemical dissolution of copper takes place and sludge was formed resulting low MRR and electrolyte contamination. NaCl was also failed to give any significant improvement in MRR. NaOH then used as electrolyte and yielded a high machining rate due its high specific conductance which leads to high chemical reaction and rapid gas film formation. Jain et al. [7] modeled electrochemical discharge as a phenomenon similar to that which happens in arc discharge valves. They simulated the ECDM process using finite element (FE) approach assuming a prismatic plasma channel having cross sectional shape of square assuming uniform heat flux distribution.

Wuthrich et.al.[8] studied the effects of voltage, tool shape and force of ECDM machining. They proposed the two regimes of the ECDM machining. The first one as 'discharge regime' (initial 200–300 μm drilling depth) which has number of discharges inside the gas film developed due to H_2 gas bubble coalescence, In this region the rate of drilling is fast (~100 μm/s). The second one is 'hydrodynamic regime' (below 300

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μm)where the drilling speed is lowered(~10 μm/s) due to less amount of electrolyte flow inside the micro-hole. Kim et al. [9] studied the effects of voltage pulse frequency and duty cycle in the machining process. They showed that ECDM process can be used with pulsed DC or Regular DC voltage. In regular DC supply the thermal energy generated due to field emission of electrons causes thermal damage and produces heat affected zone. With pulsed DC voltage supply, surface quality is improved as there is surface damage. They concluded that high frequency and a small duty ratio are essential to get a precise hole with only a small amount of thermal damage, with a compromise in removal rate. They also revealed that the tool wear rate and the overcut increase with a smaller diameter tool.

Yang et al. [10] fabricated the stainless steel, tungsten carbide, and tungsten tool-electrodes using wire electrical discharge grinding (WEDG).They suggested that wettability of tool material affects the merging of gas bubbles and formation of the gas film, machining quality and micro-hole features obtained using gravity feed ECDM. It is found that tungsten has highest and stainless steel has the lowest machining speed at their optimal machining voltage. Jiang et al. [11] simulated the current density distribution in the tool electrode and determines the effectiveness of tool geometry for the micro-hole drilling by gravity feed ECDM process. The material is removed due to high current density across the periphery of cylindrical tool and it forms fringes whereas with tapered tool, it is possible to focus the discharge into a concentrated region. They suggested that tool wear of tapered tool can be a problem if the machining time is long. The temperature of the tip will rise too high as the spark will be concentrated at the tip and it will reach up to melting point that will be responsible for tool wear. Yang et al. [12] showed the application of spherical tip tool to which leads to an increase in machining time and opening diameter with increase in machining depth. With this shape of tool machining accuracy and efficiency has increased and its due to the fact that area of contact between tool and work-piece gets shortened letting the electrolyte flow smoothly. They showed the comparison in machining performance of cylindrical tool-electrode and spherical tool-electrode and found the reduction in machining time and micro-hole diameter with increase in micro-hole depth. Pankaj Kumar et.al.[13] experimentally predicted the effective pulse duration as 250 Hz and effective duty factor as 25%. At these values they observed continuous supply of thermal energy for material removal with optimum cooling time. Further, an increase in duty factor increases aspect ratio. They recommended using longer pulse duration for NaOH electrolyte as NaOH provides excessive thermal energy.

From the detailed literature study, it is found that most of researchers have used ECDM machining on various non-conducting materials. Most of the works are reported with gravity feed type of ECDM. Very less work is reported on constant velocity feed type of ECDM. Very few researchers worked on the effect of pulse frequency and duty factor on micro hole quality. So the present investigation focuses on ECDM machining (constant velocity feed mechanism) of micro holes in soda lime glass considering the effects of the input process parameters, namely voltage, pulse frequency and duty ratio on the micro hole top and bottom diameter.

2. EXPERIMENTAL DETAILS

The ECDM experimental set up consist of main sub-systems such as machining chamber, motion controller and power supply(see Fig.1) .The Main machining chamber which is made up of acrylic having dimension 14 x 14 x6.5 cm3 contain wafer holding vice in which glass wafer is placed and it is supported with the help of tightening screws.

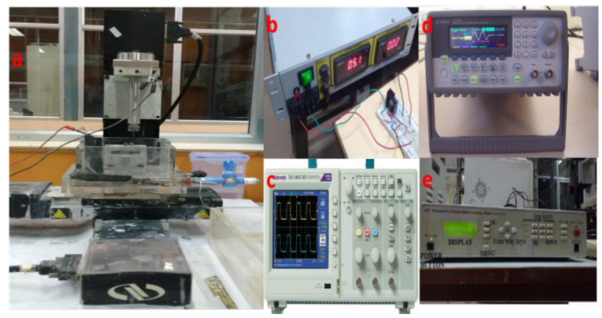

Fig. 1. ECDM experimental set-up (a) XY stage (b) DC power supply with pulsed generating circuit(c) Oscilloscope (d) Function generator (e) XYZ Motion controller

Machining chamber has inlet and outlet ports which is made to enable the flow of electrolyte through the chamber while machining process. Universal motion controller used to control the motion in X, Y and Z direction in order to align work-piece and tool so that machining can be performed in the desired location. Newport ESP 300 controller is employed. It can be operated in manual or command mode. High speed or low speed jog is available with the manual feed interface. Tool holding unit is connected to z axis of the controller. Tool holder consists of a collet and collar screw to hold the tool electrode. Work-piece holding vice is used to keep the glass wafer in the machining chamber with the tightening screws. Pulsed power supply is provided for the all the experiments.

Table 1

ECDM process parameters

Process parameters	Range of Values
Pulse Frequency (F)	100 to 10000Hz
Duty ratio (DR)	50%,60 % & 70%
Applied voltage(V)	55 V , 60 V & 65 V
Initial tool- work-piece gap(G)	In contact ,0.05mm
Feed for tool	0.0005mm/sec
NaOH Electrolyte Concentration(C)	10 % to 20%
Inter-electrode gap(IEG)	2.5 cm
Counter Electrode	Graphite 16x16x5 mm^3
Glass work-piece thickness	0.4 mm; Soda-Lime
Glass work-piece size	20 × 25 mm
Immersion Depth	0.3mm above work-piece

These experimental parameters were obtained by preliminary trial experiments performed before the main experiments. These parameters are highly dependent upon several factors: tool immersion depth, tool size, concentration, experimental limitations. Based on these factors, range of input parameters has been finalized. Initially we have done experiments at varying NaOH concentrations starting with 10%, 20% and 30%; however, at 30% concentration, electrolysis procedure was very severe which produces thermal cracks in the glass. Also toxic vapors were forming which was causing lot of hazardous environment to the users. It is observed that lower concentration was better to achieve lower overcut and lower heat affected zone. Hence 10% NaOH concentration was used for the experiments. As per the observation, no electric sparks were formed upto 53 volts which is the critical voltage. Hence machining voltage varied in the range of 55V to 65V. Upper limit of the voltage used is 65V, because above this voltage sparking becomes drastic, which leads to breakage of the glass. Tool feed was selected as 0.5µm/sec for the experiments, which was the safe value to avoid the breakage of the glass work-piece. Effect of Pulse frequency and duty ratio is not explained well in the literature .Hence these 2 parameters varied taking 3 levels each.

As the copper is ductile material, it was difficult to machine with a smaller diameter of the copper tool and tool straightness and its failure during the machining was a big problem. Also, micro turning was a big challenge to produce smaller diameters. A needle-shaped stainless steel tool (see Fig.2) is then used for further experiments which also has the advantage of high energy density as compared to the cylindrical tool. Also, it is stiff enough to avoid any bending during the drilling operation and has negligible tool wear.

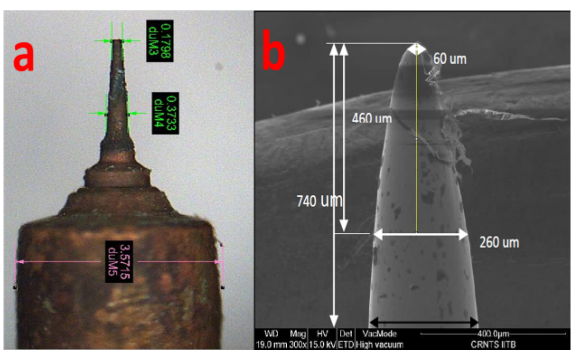

Fig. 2. Tool electrodes (a) Cu micro-turned tool (b) Steel Needle tool

3. RESULTS AND DISCUSSIONS

To investigate the influence of process parameters such as voltage, pulse frequency and duty ratio on micro hole top and bottom diameter, a set of experiments is designed in which experiments were performed varying one factor at a time. A tapered stainless steel tool of tip diameter of 100 microns is used for each set of experiments conducted in 10% aqueous NaOH solution. Other parameters such as inter-electrode gap, tool immersion depth, electrolyte concentration are kept as constant throughout the process. Soda lime glass of dimension 22×25×0.4 mm is used as a work-piece to create micro holes by the ECDM process. During the experimentation, one parameter was varied keeping other parameter fixed at a certain level. Total 27 sets of experiments are carried out. Each set of experiment is repeated 3 times. The average value is taken for the analysis.

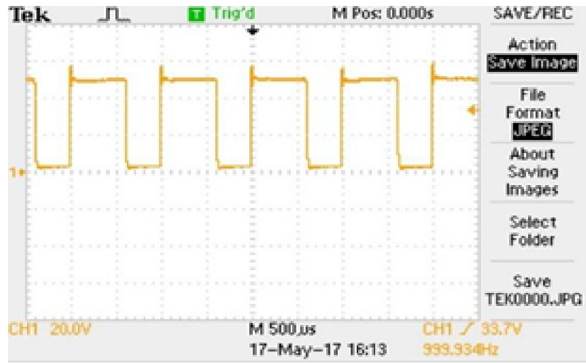

Fig. 3. 50V Rectangular pulsed voltage cycle with 1000Hz frequency

Initial gap between the tool and the work-piece was set to be zero and velocity feed was then given with the help of Newport controller while machining in order to drill the hole up to the depth of 0.4 mm. The level of the electrolyte was maintained just up to the upper surface (approximately 0.5mm) of the glass work-piece to ensure the constant tool immersion depth. Velocity feed is used while machining and it is observed that in order to avoid the breaking of glass work-piece or bending of tool electrode, feed rate has to be lower than the mean material removal rate of the ECDM process. It is observed during the experiments that at low voltage and high frequency, feed needs to be too low i.e. less than 0.5 µm/s in order to machining up to full depth. Each experiment is conducted three times for a given set of experimental condition and mean value has been taken to obtain the influences of the input parameter and plotted to analyze the machining performances.

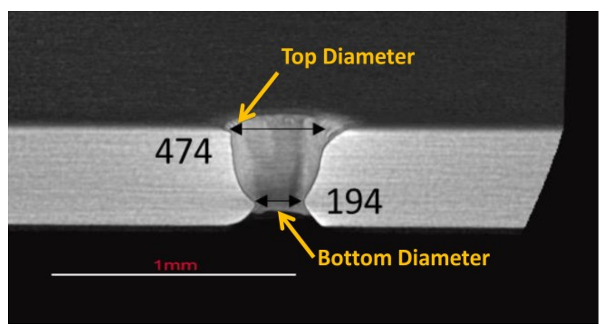

Fig. 4. Typical tapered micro hole profile (FDXM image)

3.1 Effect of duty ratio on the hole diameter

Pulse width modulation of applied voltage has two components-duty ratio and pulse frequency. The effect of the duty ratio of top diameter and bottom diameter for a different set of applied voltage and pulse frequency is shown in the Fig.5.

Material removal rate will decrease if the Voltage pulse frequency increases and duty ratio decreases [9].So as duty ratio increases pulse-on time increases, which means more spark energy is provided for machining. But since frequency is varied from 100Hz to 10000Hz, material removal and hole diameter is varied .100 Hz with 50% duty cycle means 5ms of on and off time. Time for Gas film formation is about 1 to 3ms [2].So it is advisable to give sufficient amount of pulse-on time in order to have sufficient time for gas film formation. Otherwise gas film won't form precisely and it may hamper the machining. So it is required to have an optimum combination of duty ratio and pulse frequency. In Fig.5a, we can see that Top diameter of the micro-hole increases as duty ratio increases at constant applied voltage of 55V .Maximum top hole diameter obtained is 1114 µm and minimum as 440 µm. Though gas film formation will get affected at higher frequency, the material removal is still higher as pulse-on time is high. In Fig.5a, 5b and 5c, it can be observed that at 100Hz frequency and 50%DR, Top diameter is minimum, which means overcut is less.

This is due to the fact that gas film formation is precise and there is sufficient time to form the gas film which leads to a stable spark.

The maximum top diameter i.e.1114 µm is obtained at the highest applied voltage-65V.Since at higher voltage material removal is high due to intense spark energy. But at same applied voltage of 65V with 70% DR and10000Hz the top diameter obtained is 480 µm. This random value of top diameter obtained is may be due to the fact that, at higher frequency spark is not stable and more random and uncontrollable machining takes place. Bottom micro-hole diameter is unpredictable due to independency from applied voltage and due to irregular chemical etching. Since it is mentioned that below 300 µm, the material removal is less depends on melting due to spark energy and more depends on chemical etching action of the NaOH electrolyte. It can be seen from the Fig.5d, 5e and 5f, at higher voltage of 65V,bottom diameter is large .Bottom micro hole diameter is smaller in case of low voltage value i.e.55V.

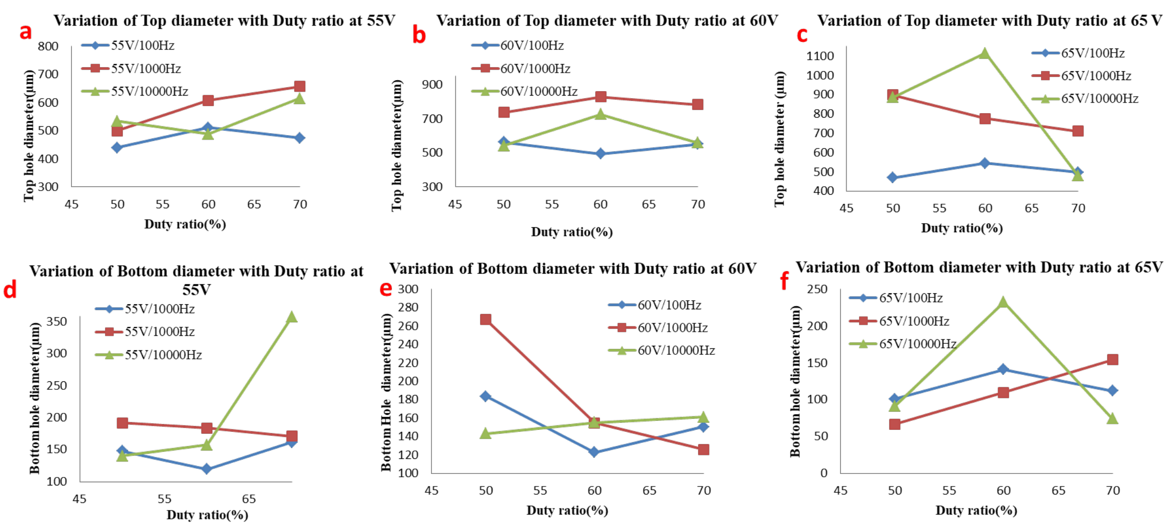

Fig. 5. Variation of Top and Bottom diameter of micro hole with respect to Duty ratio

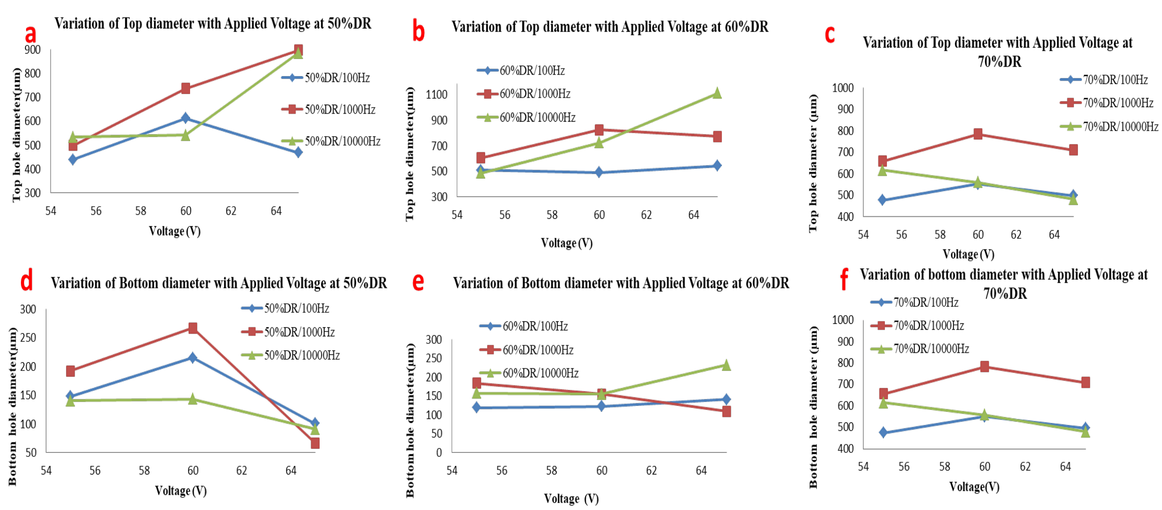

Fig. 6. Variation of Top and bottom diameter of micro hole with respect to applied voltage

3.2 Effect of applied voltage on the hole diameter

It is suggested in the literature that applying the pulsed voltage reduces the duration to which spark occurs and it gives time to drilling regime to cool. This enhances the surface quality of the drilled holes but reduces the material removal rate.Fig.6a, it can be seen that as applied voltage value is increased from 55V to 65 V the top micro-hole diameter is increased, irrespective of the increment in pulse frequency. It is due to the fact that as voltage increase, no.of sparks goes on increasing which leads to higher MRR and fast machining. Still at higher voltage and higher frequency the process becomes unstable since gas film formation is affected by the higher pulse frequency. Least average top diameter of micro-hole is 440 µm which is obtained at 55 volts with 50%DR and 100Hz frequency. In Fig.6c, it is observed that at 55Volts with 70%DR and 100Hz frequency the hole diameter is 474 µm. This indicates that 100Hz frequency is optimum to get lower top diameters. This diameter is larger by 34 µm as compared previous least diameter. This is because of the 70%Duty ratio which leads to higher pulse-on time. From Fig.6a and 6c, it can be observed that for both 50% and 70%DR, micro hole top diameters are larger. These larger values are at 1000 Hz pulse-frequency. The reason behind this may be the fact that at this pulse frequency the material removal is higher more no. of sparks happens. At 10000 Hz, the sparking turns out to be random and unstable; hence material removal is not uniform. Though the bottom hole diameter is more depends on the chemical etching of the electrolyte, certain pattern is observed (see Fig. 6d and 6f).The bottom diameter first increases and then decreases. The possible reason maybe that chemical etching action is higher at 60volts and some amount of spark energy may also be responsible for material removal.

3.3 Surface topography of micro holes

To investigate the variation among the holes at the different process conditions, surface topography is captured through SEM. Three holes are drilled at the process condition of 60 V/100 Hz/70% DR, 55V /10 kHz/70% DR and 60 V/100 Hz/ 60%DR respectively. Fig.7 shows the top view of the holes and corresponding holes edges.

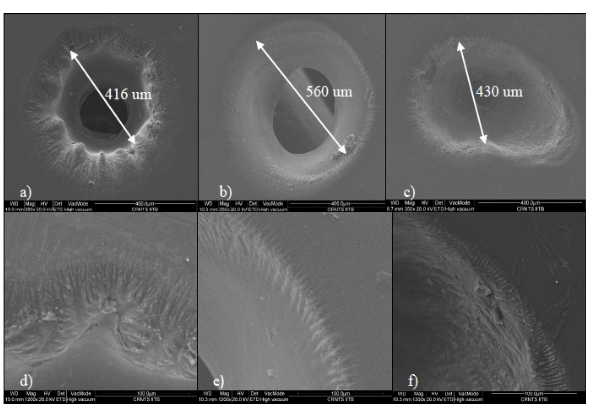

Fig. 7. SEM images of micro-hole samples (a,d) 60 V/100 Hz/70% DR, (b,e) 55V /10 kHz/70% DR (c,f) 60 V/100 Hz/ 60%DR

Fig.7(a, d) and (b, e) confirm the fact that converting the energy into small packets i.e. increasing pulse frequency can reduce the roughness of the micro-holes but the increment in both top and bottom diameter is due to the large tool travel. MRR is relatively less at lower voltage and higher frequency and hence, more is the machining time that makes the tool to travel more in the case of constant velocity feed. As the tool is a taper, more tool travel leads to the larger entrant diameter and also large exit diameter. Fig.7 (a, d) and (c, f) show the holes drilled at different duty ratio keeping the applied voltage and pulse frequency same. Heat affected area at higher duty ratio is much more than at lower one. It means the increased pulse durations affected the more regions around the micro hole. Larger hole diameter in the latter case is due to the same reason that MRR is low and hence, more tool travel and so the larger entrant hole diameter due to tool taperness.

4 CONCLUSIONS

Experimental investigation of ECDM machining is performed and values of the output responses are recorded and plotted graphically. Variation of hole diameters for different values of the applied voltage and duty ratio is observed. It is concluded that increasing the applied voltage will increase the hole diameters as the amount of effective thermal energy is increased that removes more material corresponding to the additional value of increased applied voltage. Duty ratio which directly corresponds to the pulse on time also increase the hole diameter with its increase in value. It also observed that difference between the top and the bottom diameter is also kept increasing. SEM images of micro holes provide the insight to the surface quality of holes. The least top hole diameter (440 µm) is obtained at 55V with 100Hz and 50% Duty ratio. Increasing pulse frequency will definitely improve the hole roughness. Smaller values of applied voltage will increase the machining time but also reduce the hole diameters and heat affected zone. Duty ratio should be in the trade-off between the machining time and surface roughness.

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