EXPERIMENTAL ANALYSIS OF MICRO-CHANNEL FABRICATION ON QUARTZ GLASS USING ECSM PROCESS

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Quartz glass has a wide role in different fields, such as micro-electrochemical systems (MEMS) and micro-fluidics equipment. Quartz glass is difficult to machine material because it exhibits brittle and non-conducting physical properties. The Electrochemical spark machining process (ECSM) is a hybrid method that offers adept and cost-effective quartz glass machining rather than other advanced manufacturing processes. In this investigation, micro-channels are formed by the Electrochemical spark milling process and observed the effects on material removal rate (MRR) and surface roughness (R_a) of different levels of input machining parameters like DC voltage, electrolyte concentration, duty cycle, and tool rotation. The experiment result shows a high material removal rate and low surface roughness through a 370 μm diameter copper tool electrode. Observation of the electrophoretic effect on increments in electrolyte concentration and its impact on material removal rate is the crucial factor of this research work, which has never been reported in previous studies on ECSM.

Keywords: ECSM; Micro-channels; MRR; Quartz.

1. Introduction

The electrochemical spark machining (ECSM) process is a hybrid technology with good potential and performance capability in machining non-conducting workpieces like quartz glass. Due to transparency, frequency stability, chemical and high-temperature resistance, quartz is extensively used in micro- electromechanical systems (MEMS), micro-optical electromechanical systems, and drug delivery devices [1]. The high percentage of SiO_2 in quartz glass offers high hardness, better corrosion, and thermal resistance than other glass [2]. Although, the high hardness of quartz glass causes poor machining, making the need for more study in the context of this material's machining characteristics.

The high hard and brittle nature of quartz glass makes limited opportunities for machining in conventional machining methods. The electric discharge machining method (EDM) can be used only on electrically conductive

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workpieces [3]. Different advanced machining methods such as laser beam machining (LBM), electron beam machining (EBM), and ion beam machining (IBM) can be used in

the machining of quartz glass. Still, the high equipment cost and significant power consumption make these machining processes costly compared to ECSM [4-5].

Different advanced machining methods such as laser beam machining (LBM), electron beam machining (EBM), and ion beam machining (IBM) can be used in the machining of quartz glass. Still, the high equipment cost and significant power consumption make these machining processes costly compared to ECSM [4- 5]. Fig. 1 expresses the framework figure of the ECSM process. The ECSM technique uses two electrodes. Both electrodes are immersed inside the electrolyte solution. A smaller-sized tool electrode is placed over the workpiece, and it has negative polarity, and a bigger-sized electrode (auxiliary electrode) has positive polarity. These two electrodes are connected with a direct current source power supply which creates a potential difference between these two electrodes. The potential difference causes hydrogen bubbles to form at both types of electrodes. On and over the critical voltage value, hydrogen bubbles merge and produce a gas film on both electrodes. This gas film works as a barrier between these two electrodes, and at sufficiently high voltage, an electric spark produces at negative polarity electrode causes material removal at workpiece [6]. Many researchers have performed experiments to investigate the machining of quartz glass on ECSM. Material removal rate and surface roughness of the quartz glass workpiece depend on the selection of electrolytes, tool material, and input machining parameter range in ECSM. Different electrolytes are commonly used in the ECSM process, such as NaOH, NaCl, $NaNO_3$, HCl, H_2SO_4[7]. Mallick et al. [8] reported high MRR with NaOH electrolyte during glass machining by ECSM. Another reason behind the preference of base electrolyte over-acidic electrolyte is the greater surface roughness of the workpiece under acidic conditions [9]. Tool electrode material and rotation have a significant role in machining on ECSM. Higher charge density on tool electrode is maintained in the machining of ECSM by considering a much greater size of positive polarity auxiliary electrode compared to tool electrode [10].

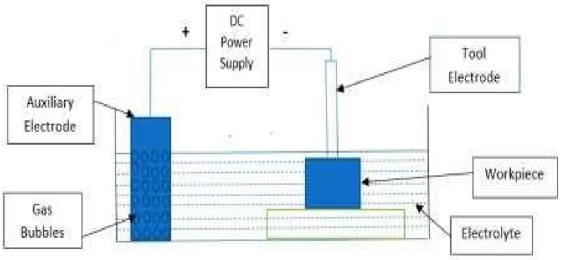


Fig. 1. The framework figure of the ECSM process

Tool electrode material should have good conductivity with high stiffness to sustain its original shape under loading conditions. Commonly used tool electrode materials are SS, tungsten carbide, copper, etc., in ECSM. The copper tool provides a better material removal rate and a good surface finish in machining quartz glass workpieces using the ECSM process [11]. Tool electrode rotation significantly affects the machining outputs such as material removal rate and surface finish on ECSM. Material removal rate and dimensional accuracy are enhanced due to more homogenous dispersed discharge energy in tool electrode rotation during machining on ECSM [12,13]. Zheng et al. [14] observed in their experiment that reduced groove width is formed on the higher tool rotation speed in the ECSM milling process due to thinner film formation of electrolyte on the elevated rate of tool rotation. The applied DC voltage straight impacts the material removal and surface roughness in ECSM. Sarkar et al. [15] concluded in their study that Among all input machining parameters of the ECSM process, the effect of applied voltage plays dominating role on material removal, over cut than other process parameters. Higher material removal rate is obtained at elevated voltage because of the transmission of high discharge energy. In rectified DC supply voltage, consistency of thermal energy in machining zone causes over-cut phenomena. Pulse voltage supply permits the cooling condition in the pulse off time, which reduces the over-cut in the machining zone [16]. Sundaram et al. [17] conducted an experimental analysis of the ECSM drilling process with a glass fiber epoxy reinforced composite workpiece. After experiments, they found the effect of duty cycle and electrolyte concentration on the heat-affected zone (HAZ) over the workpiece. Thinner gas thickness is formed at a low duty cycle value, resulting in low discharge energy and HAZ.

Lowering the duty cycle of pulse ECDM results in thinner gas films and longer gas film formation times, which in turn lower sparking energy and frequency. Smaller hole diameters and lower HAZ are the effects of this, particularly for low-duty cycles. There is a duty cycle and electrolyte level combination that works best. Moreover, a higher electrolyte content will result

in a smaller hole diameter at low duty cycle and a higher HAZ. Nguyen et al. [18] reported that in the ECSM milling process of quartz workpiece with a low concentration of electrolyte, greater thermal energy is generated in the machining zone due to low resistance between tool electrode and workpiece. For getting high depth microchannels (depth greater or equal to 500μm), a multi-pass milling operation is used [19]. Multi-pass milling operation requires a high duty cycle supply with a greater value of electrolyte concentration. Getting machining with an excellent surface finish of the workpiece is still needed for more study in ECSM. Oza et al. [20,21] performed a wire electrochemical spark machining process (W- ECSM) with a quartz workpiece and reported a better surface finish with a zinc layered brass wire electrode. An additional advantage of using zinc coating is enhancing strength against wire breakage. Some researchers worked with abrasive particles electrolytes to improve the surface finish in the ECSM process. Electrolyte with SiC abrasive particles enhances the surface finish of the workpiece in W- ECSM because abrasive particles in electrolyte raise the value of critical voltage, results lower spark energy and micro-cracks in machining [22]. Ladeesh and Manu
[23] investigated machining parameters effects in machining of borosilicate glass through grinding aided electrochemical discharge engraving. The authors concluded that tool feed rate is the most significant factor in channel overcut and voltage is the prime machining input parameter which effects the surface roughness of channel. Singh et al. [24] focused their study towards effect on electrolyte nature on fume generation. They observed that fume mass concentration is increased with enhancement in electrolyte concentration. Guo et al. [25] and Goud et al. [26] perform research to improve the machining quality in ECSM. Above mentioned
review study of previous research shows a need for more experimental investigation and modelling approach in the machining area of ECSM to get desired results of material removal and surface finish. To improve the surface finish and material removal rate of quartz workpiece, copper material is used for tool electrode and auxiliary electrode in present experimental work on ECSM. Quartz workpiece is broadly used in the scratch-free touch screen of smartphones, micro electro- mechanical systems (MEMS), and drug delivery systems. Quartz workpiece has high hardness and brittleness, which causes poor machinability in conventional machining processes[27]. These limitations make more importance of experimental and modelling analysis of ECSM processes.

2. Workpiece Material and Experimental Setup

Experimental work was executed on a self-developed setup of ECSM. There are mainly machining unit and power supply unit in this setup. Fig.2

demonstrates the developed ECSM setup.

(a) Machining Unit of ECSM setup

This unit has a machining chamber, which is made of acrylic material. The corrosion resistance property of acrylic makes it suitable for electrolyte-filled machining chamber. There were 12V DC supply three stepper motors for providing three-axis motion on ECSM setup. The setup is interfaced with a computer, and axial movement is controlled by CNC USB controller software. This setup uses a copper electrode of 370 µm diameter as a tool electrode. A DC motor is used for the rotation of the tool electrode. An auxiliary electrode of 2 mm diameter made of the copper electrode is used in this experiment. The gap between the tool and auxiliary electrodes was maintained at 50mm in all experimental observations. The dimension of the quartz glass workpiece was 50mm x 25mm x 2mm, and a copper electrode of 370µm diameter is used as a tool electrode with NaOH electrolyte on ECSM setup. The machining time for the present investigation was two minutes with 2.5mm/min tool travel speed. Table 1 presents the characteristics of the quartz glass workpiece.

(b) Machining Unit of ECSM setup

The power supply unit of this setup has the facility to produce a pulse voltage DC power supply. In this experimental work, a range of applied voltage is 45 V to 55 V. Positive terminal is connected to the auxiliary electrode, and the negative terminal is connected to the tool electrode. Table 2 shows the specifications of the power supply unit, which is used in the ECSM setup.

Table 1

Characteristics of the quartz glass material

Young's modulus	108 GPa
Density	2.2 *gm/cm*^{3}
Softening Temperature	1700^0*C*
Thermal Conductivity	1.38 *W/mk*

Table 2

Specification of power supply unit of ECSM setup

Pulse Power Supply	
Input	Three-phase AC, 415 *V*, 50 *Hz*
Output Voltage	0-300 *V*
Output Current	Up to 15 *amp*
Pulse on Time	50 to 1000000 *micro- seconds*
Pulse off Time	50 to 1000000 *micro- seconds*
Pulse Rise Time	2 *micro-second*
Pulse Fall Time	*2 micro-second*

3. Machining and Methods

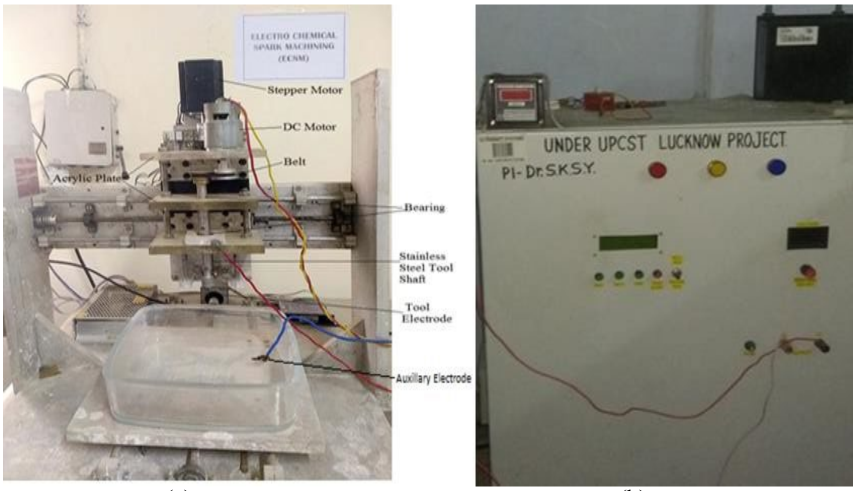
In the present research paper, MRR and surface roughness are investigated during the machining of a Quartz glass workpiece on an electrochemical spark milling process using Full Factorial Design of experiments. In Full Factorial Design, factors with levels are arranged in such a manner that the design of the experiment shows all possible sets of process parameter combinations. Full factorial design covers the main effects as well as interaction effects. This may result in more effective experimentation and enhanced comprehension of the system under this study work. Before performing the main experiments, pilot experiments were completed on different values of applied voltage, electrolyte concentration, duty cycle, and tool rotation. Pilot experiments concluded that below 45 V voltage and 19% electrolyte concentration of NaOH, quartz glass cannot be machined on ECSM because quartz glass has a high softening temperature, and above 55 V voltage and 29% electrolyte concentration, the tool electrode is melted due to high heat energy generation. It is found in pilot experiments that tool electrode rotation provides better MRR and surface finish in comparison to stationary tool electrodes during machining on ECSM. The range of tool electrode rotation is selected from 400 RPM to 800 RPM with a duty cycle range of 0.75 to 0.89 because, under this range, flashing of electrolyte impacts significantly on MRR and surface finish with a moderate heat-affected zone over the workpiece.

Based on pilot experiments, levels of input process parameters were decided. Table 3 shows input process parameters with their levels. Table 4 and Table 5 show the experimental parameters of this research work. Here are four factors and three of their levels used in this experimental work. According to the expression, $\text{level}^{\text{factor}}$, a total of eighty-one main experiments are performed.

It was reported in pilot experiments that copper tool electrode provides a better surface finish on quartz glass workpiece through milling. Due to this reason, the copper tool of 370 μm size is used as a tool electrode in this investigation. Due to the low stiffness of copper tool material, smaller than 370 μm diameter cannot be used as a tool electrode. An auxiliary electrode of copper 2 mm diameter is used in this work. The selection of the same materials of tool electrode and auxiliary electrode reduces the tool deposition rate during machining on ECSM. The tool electrode was immersed into electrolytes at a depth of 1 mm.

The quantity of material removed from the workpiece per unit of time is known as the material removal rate (MRR). MRR is a crucial performance indicator which explains the ECSM process machining production. The input process parameters such as voltage, electrolyte concentration, duty cycle and tool rotation affect MRR. MRR is calculated by measuring the weight of the workpiece before and after the machining. In this research work, the weight of the workpiece is observed through a Denver SI 234 weight machine with an accuracy of 0.01 mg. Equation (1) is used for measuring MRR. Every measurement was taken three times, and the mean of these was considered a final measurement. Micro-channel surface roughness is measured with the Mitutoyo Surftest SV-2100 instrument. A digital laser tachometer measures tool rotation during the experiment. Here, X is MRR in mg/min, B is the weight in mg of the workpiece before machining, A is the weight in mg of the workpiece after machining and T is the time in minutes.

$$X = \frac{B-A}{T} \tag{1}$$



(a) (b)

Fig. 2. Experimental Setup: (a) ECSM machining setup (b) Power Supply Unit

Table 3

Input Process Parameters with their levels

Input Process Parameters	Level		
	First	Second	Third
Voltage(V)	45	50	55
Duty Cycle	0.75	0.82	0.89
Tool Rotation (RPM)	400	600	800

Table 4

Experimental Constant Parameters

Tool electrode	370μm diameter copper
Auxiliary electrode	copper
Workpiece	quartz plate

Electrolyte	NaOH
Machining Time	2 min
Tool travel rate	2.5*mm/min*

Table 5

Experimental Variable Parameters

Variable Parameters	
Voltage	45V,50*V*,55*V*
Duty Cycle	0.75, 0.82,0.89
Tool Rotation	400RPM,600RPM,800RPM
Electrolyte Concentration	19*wt%,24wt%,29wt%*

4. Result and Discussions

In this study, Full Factorial Design is considered for performing experiments to investigate machining analysis through all possible sets of process parameter combinations. To observe the effect of input machining parameters on MRR and Surface roughness, curves are plotted in this section in which one parameter effect is observed on MRR and Surface roughness keeping other input parameters constant. Curves through this approach provide a better understanding of the impact of input machining parameters on output machining parameters in ECSM.

4.1.Effect of Different Parameters on MRR

The impact of voltage is observed on the material removal rate, surface roughness, and width of the heat-affected zone in this study. It is investigated that MRR is enhanced on increment in the value of the applied voltage at 400 RPM, 29% electrolyte concentration, and 0.75 duty cycle. Since spark intensity increases as increases in voltage, which creates an increment in the melting of the workpiece. The tool travel speed is constant at 2.5 mm/min. DC pulse voltage power supply is used in this study. The low voltage causes low thermal energy, so no material removal was reported on the Quartz workpiece below 45 V. In Fig. 3., MRR increases as the applied voltage enhanced. From 45 V to 50 V, MRR is enhanced by 41.66%, and in the range of 50V to 55 V, MRR is increased by 58.33%. MRR has a sharp increment in the domain of 50V to 55V compared to 45V to 50V due to high thermal energy generation in the range of 50V to 55V.

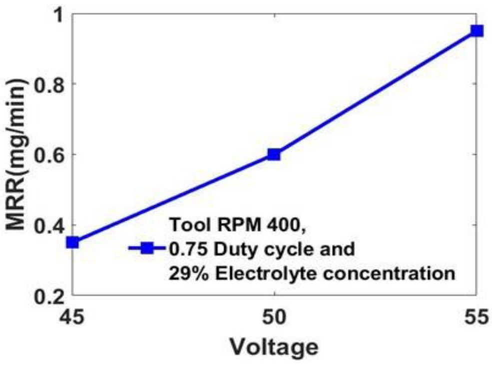


Fig. 3. Variation of MRR (mg/min) with different Applied DC Voltage

Fig. 4 displays the effect of tool rotation on MRR with input machining conditions 50 V, 29% electrolyte concentration, and 0.75 duty cycle. This study observed that MRR is enhanced by 36.36% with increments in tool rotation in the range of 400 RPM to 600 RPM. The increment in MRR enhances the electrolyte flashing with increased tool rotation in the machining zone. Flashing of electrolytes improves ECSM performance and MRR. On increment tool rotation from 600 rpm to 800 RPM, MRR is decreased by 20% in this particular region. In the 600 RPM to 800 RPM region, the high speed of tool rotation reduces the stability of sparking caused by low MRR. MRR is reported 0.55 mg/min,0.75 mg/min, and 0.60 mg/min at 400 RPM,600 RPM, and 800 RPM, respectively.

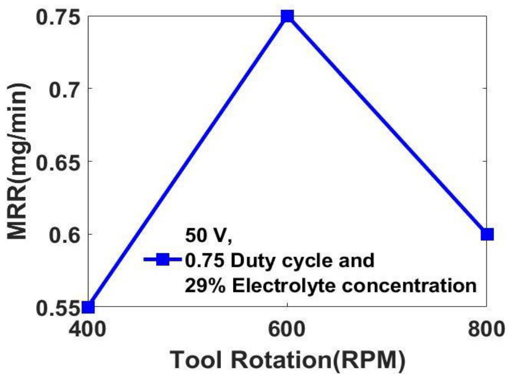


Fig. 4. Variation of MRR (mg/min) with different tool rotations

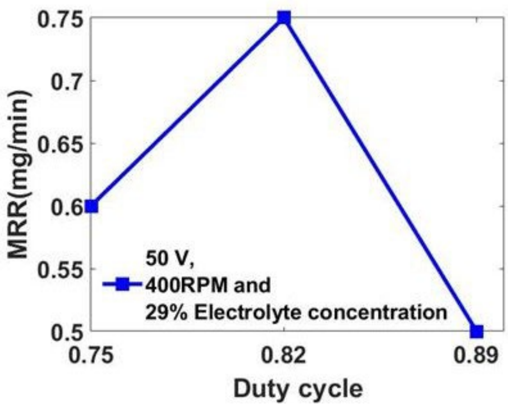


Fig. 5. Variation of MRR (mg/min) with the different duty cycle

Fig. 5 shows the duty cycle's effect on MRR with input machining conditions 50 V, 29% electrolyte concentration, and 400 RPM in the ECSM process. There are two ranges in this figure. In the first region, from 0.75 to 0.82 duty cycle, MRR is increased because of enhancing discharge energy. This is because more discharge energy facilitates the melting mechanism of the workpiece. In the second region, from 0.82 to 0.89 duty cycle, MRR is decreased as the duty cycle increases because the time of evaporation of the melting material of the workpiece in the machining zone is lower than the 0.89 duty cycle compared to the 0.82 duty cycle. So in the first region, discharge energy acts as a dominating factor, whereas in the second region, time for evaporating the melting workpiece is a dominating factor for MRR.

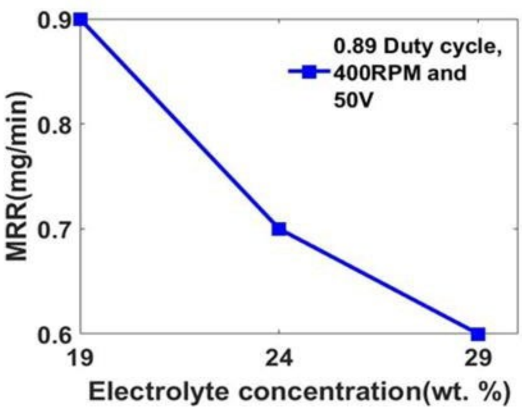


Fig. 6 Variation of MRR (mg/min) with the different electrolyte concentrations

It can be seen in Fig. 6 that MRR decreases with an increment of electrolyte concentration. There is a high interionic attraction at higher concentrations of strong electrolytes due to a large number of ions in a definite volume. Numbers of ions with opposite charge neighbour each ion. On application of potential, both types of ions move in opposite directions. Since they are in solvent position so due to the motion of these opposite natures' ions, friction is produced in between layers of respective ions. This friction causes a low speed of ions, results in low conductance. Hence MRR is decreased with increment of electrolyte concentration due to the low conductance of electrolytes. This effect is called as Electrophoretic effect. Fig.7 shows the Electrophoretic effect.

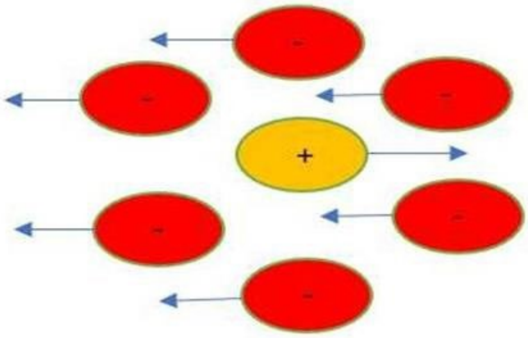


Fig. 7 Electrophoretic effect

4.2. Effect of Different Parameters on Surface Roughness

It is observed that surface roughness is reduced on raise in the applied voltage value at 400 RPM, 29% electrolyte concentration, and 0.75 duty cycle. Due to its high melting point temperature, the quartz glass workpiece requires high heat energy for machining operation through ECSM. At 45 V, surface roughness is maximum because a sufficient amount of heat is not transmitted to the quartz glass workpiece due to low applied voltage, resulting in rough surface formation of micro-channels. An adequate amount of heat is transferred on the machining surface on increments in voltage from 50 V to 55 V, causing smooth channel formation. Fig.8 shows surface roughness (S_R) values of 3.48 μm,2.74 μm, and 2.54 μm on applied voltage 45 V, 50 V, and 55 V, respectively.

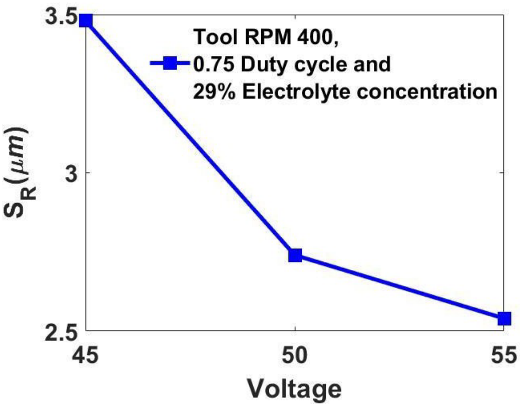


Fig. 8 Variation of S_R (μm) with different Applied DC Voltage

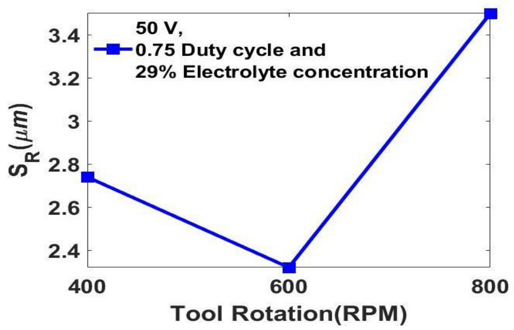


Fig. 9. Variation of S_R (μm) with different tool rotations

Fig. 9 shows the effect of tool rotation on surface roughness (S_R) with input machining conditions 50 V, 29% electrolyte concentration, and 0.75 duty cycle. Electrolyte flashing and spark stability play an important role in deciding the workpiece's surface finish in ECSM. On increment of tool rotation from 400 RPM to 600 RPM, electrolyte flashing is improved, resulting in better chemical action on the machining surface, causing low surface roughness at 600 RPM. On increment tool rotation from 600 RPM to 800 RPM, surface roughness is increased by 50.8% because, in this region, spark stability is highly reduced due to high tool rotation speed. Lack of stability in the spark causes low discharge energy transfer towards the machining zone, increasing surface roughness. In this region, lack of stability in spark plays a dominant role over electrolyte flashing. Surface roughness (S_R) values are 2.74 μm, 2.32 μm, and 3.50 μm on 400 RPM, 600 RPM and 800 RPM, respectively.

Fig. 10 shows the duty cycle's impact on surface roughness (S_R) with input machining conditions 50 V, 29% electrolyte concentration, and 400 RPM in the ECSM process. There are two ranges in this figure. In the first region, from 0.75 to

0.82 duty cycle, surface roughness (S_R) is increased by 24.81% because of high discharge energy on the machining zone, which improves MRR but damages the workpiece's surface finish through the heat-effected zone. From 0.82 to 0.89 duty cycle, surface roughness (S_R) is decreased because the time of evaporation of the melting material of the workpiece in the machining zone is lower at 0.89 duty cycle, resulting in lower cavity formation in the micro-channel. Surface roughness (S_R) values are 2.74 µm, 3.42 µm and 2.94 µm on 0.75 duty cycle,0.82 duty cycle, and 0.89 duty cycle, respectively.

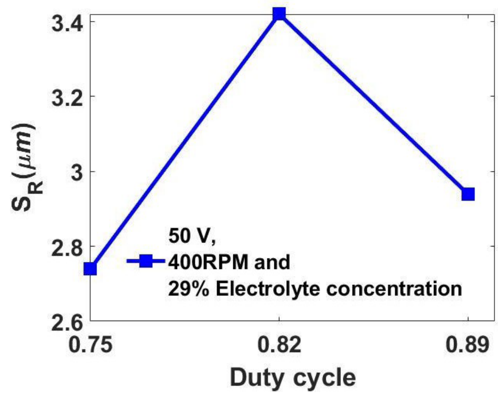


Fig. 10. Variation of S_R (µm) with the different duty cycle

Fig. 11 shows that surface roughness (S_R) increases with an increment of electrolyte concentration from 19% to 24% due to the electrophoretic effect. The electrophoretic effect produces low conductance of electrolytes, resulting in a lack of discharge energy passing towards the machining zone from the tool electrode through the electrolyte. The presence of an insufficient amount of discharge energy causes MRR through incomplete melting of the workpiece, which produces higher surface roughness. Beyond 24% electrolyte concentration, an increment in electrolyte concentration reduces surface roughness (S_R). In this region, chemical action dominates low electrolyte conductance, reducing surface roughness (S_R) by 5.80%. Surface roughness (S_R) values are 1.91 µm, 3.10 µm, and 2.92 µm on 19%,

24%, and 29% electrolyte concentrations with 50 V, 400 RPM, and 0.89 duty cycle.

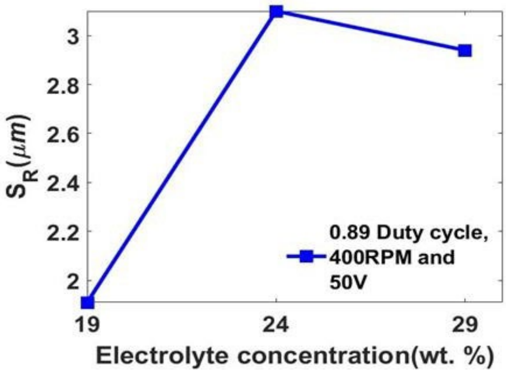
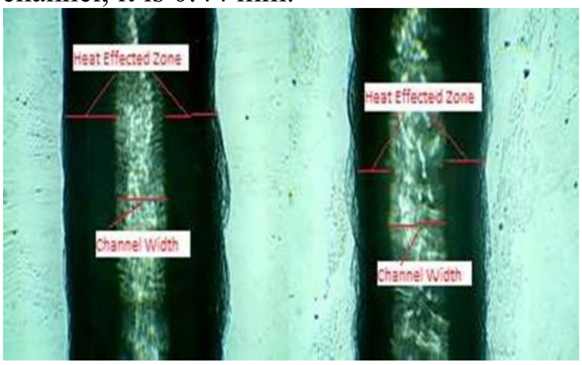


Fig.11 Variation of S_R (μm) with the different electrolyte

4.3 *Optical Microscope and Scanning Electron Microscope Images*

The current research work uses optical microscopes and Scanning Electron Microscopy images to understand the machining outputs in micro-channels fabrication. The optical microscopic images shown in Fig.12 indicate heat-affected zones and channel width at different machining conditions. The increment in the duty cycle from 75% to 82% causes enhancement in MRR and produces a greater width of heat affected zone due to high heat energy impinging on the machining zone. Fig. 12 (a) and (b) show these results in which heat affected zone width at 75% duty cycle lower than 82% duty cycle.

Fig. 13 demonstrates the SEM image of the micro-channel on 50V, duty cycle 82%, 400 rpm, and 19% electrolyte concentration. There is a circular shape tool mark in the starting, which is created due to physical contact between the tool and workpiece during sparking. In starting width of the channel is 0.53 mm, and at the end of the channel, it is 0.44 mm.



(a) (b)

Fig. 12: Microscopic Images of microchannels at (a) 50 V, duty cycle 0.82, tool rotation 400 rpm

(b) 50 V, duty cycle 0.75, tool rotation 400 rpm, and 29% electrolyte concentration

The width of the channel is decreased on moving from right to left along the length of the micro-channel because, during machining, tool wear occurs so the gap between the workpiece and tool electrode is increased. Heat-affected zone width is lesser in 0.75 duty cycle compared to 0.82 at the same other machining conditions since at 0.75 duty cycle discharge energy is lesser compared to 0.82 duty cycle.

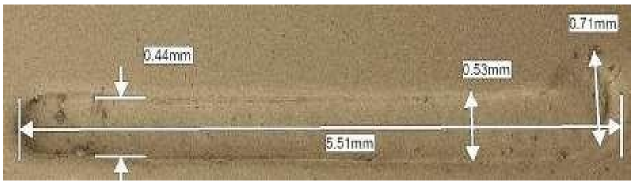


Fig. 13: SEM images of microchannels at 20X on 50 V, duty cycle 82%, tool rotation 400 rpm 19% electrolyte concentration

5. Conclusions

In this research work, an experimental analysis of micro-channel fabrication through ECSM is carried out on a quartz workpiece with a 370 µm copper tool electrode to observe the effect of input machining parameters on output response. The following conclusions are drawn based on the experimental outcomes on material removal rate and surface roughness.

- 370 µm copper tool electrode is used successfully without wire bending problem in this experimental work.
- At higher supply voltage, discharge energy is larger, resulting in a higher melting and material removal rate than at lower voltage. Material removal rate enhances 171.42% at 55 V compared to 45 V.
- The material removal rate is decreased with enhancement in electrolyte concentration due to the Electrophoretic effect. On increment electrolyte concentration, from 19% to 29%, the conductance of electrolyte is reduced, resulting in a 33.33% low material removal rate at 29% electrolyte concentration in comparison to 19%.
- On increment of tool electrode rotation from 400 RPM to 600 RPM, material removal rate first increases up to 36.36% due to better flashing of electrolyte in machining zone, but beyond 600 rpm tool electrode rotation, material removal rate decreases up to 20% due to unstable spark.
- There are two regions in the variation of material removal rate with duty cycle. In the first region, when the duty cycle changes from 75% to 82%, the material removal rate increases to 25%. When the second region's duty cycle varies from 82% to 89%, the material removal rate decreases up to 50%. In the

first region, the material removal rate is enhanced because discharge energy increases with enhancement in the duty cycle. The material removal rate decreases in the second region due to less evaporation time available for a melting material from the machining zone.

- Quartz glass workpiece has a high melting point temperature. For complete material removal through spark phenomena, quartz workpiece requires high heat energy. From 45 V to 55 V, the surface roughness (SR) of quartz glass workpiece reduces up to 27.01% because, at high voltage, an adequate amount of heat energy can transfer towards the workpiece for material removal through melting phenomena in ECSM, which improve surface finish.
- Tool rotation from 400 RPM to 600 RPM reduces the surface roughness by 15.32% due to better flashing of electrolytes, which enhances chemical action. In the second region, spark stability reduces from 600 RPM to 800 RPM, which causes uneven material removal through thermal phenomena in ECSM. Uneven melting of the workpiece increases surface roughness (SR) up to 50.86% in this region.
- On increment in the duty cycle from 0.75 to 0.82, excess discharge energy falls on the machining zone, producing thermal cracks resulting in up to 24.81% hike in surface roughness. Further increment in the duty cycle reduces surface roughness due to less evaporation time for melted workpiece material in the machining zone. In the second region, surface roughness reduces up to 14.03%.
- On increment electrolyte concentration from 19% to 24%, surface roughness increases up to 62.31% due to the electrophoretic effect, but further increment reduces surface roughness up to 5.80% in 24% to 29% electrolyte concentration region.
- The experimental results of micro-channel fabrication are significantly affected by the applied voltage, electrolyte concentration, and tool rotation.
- Optical microscope images show a greater width of a heat-affected zone on high- duty cycle levels. SEM image indicates micro-channel width decreases along the tool travel direction due to tool electrode wear during machining in ECSM.

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Nomenclature

ECSM	: Electrochemical Spark Machining
MEMS	: Micro-Electrochemical System
MRR	: Material Removal Rate

SR : Surface Roughness
LBM : Laser Beam Machining
RPM : Rotation per Minute

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