Review on Micromachining of Pyrex glass using Wire-ECDM

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Abstract- Pyrex glass has a huge range of applications such as micro optics, mechanical inertial sensors, micro-pumps, micro fluidic devices, biochip etc because of its excellent physical and chemical properties such as high chemical resistance, heat resistance, high electrical isolation, large optical transmission range, biocompatibility, low thermal and electrical conductivity, good chemical stability. Due to the hardness and brittleness properties, Pyrex glass has poor machinability. It is very complicated to machine Pyrex glass by using conventional processes. Travelling wire electrochemical spark machining (TW-ECSM) is an emerging technique for micromachining of non-conductive materials. In TWECSM, the material of the workpiece is melted, vaporized and eroded due to the transmission of spark energy to the workpiece. Surface roughness is a very important aspect if we are doing micromaching of a material. The literature reveals the work done by various researchers for the micromachining of Pyrex glass. However very less work has been done on Pyrex glass. So in this paper, work done by various researchers on Pyrex glass, Use of TW-ECDM for micromaching is reviewed, scopes for further research have been identified.

Keywords – Pyrex glass, TWECDM, Micromachining, nonconductive, Surface roughness.

I. INTRODUCTION

The micro fabrication of Pyrex glass is one of the key processes in micro-electro-mechanical-system (MEMS) and other modern industries because of its particular properties such as transparency, chemical resistance, biocompatibility and easily bonding with silicon wafers. Micro fluidic technologies have seen tremendous growth over the last few years. However, it is difficult to fabricate complex structures with a high aspect ratio by using mechanical micromachining methods due to the hard and brittle properties of glass. Recently, electrochemical discharge machining (ECDM) has been developed to overcome such material machining requirements. The process can be described as following. The glass, tool electrode (cathode) and auxiliary electrode (anode) are immersed in an electrolyte solution (typically sodium hydroxide or potassium hydroxide). A DC power source is applied between the tool electrode and auxiliary electrode. When the applied voltage is higher than the critical voltage, the electrolysis bubbles coalesce into a gas film to isolate the tool from the electrolyte. Discharges are generated between the tool and the surrounding electrolyte. The heat generated by those discharges and chemical etching contribute to the eroding of the workpiece to be machined. This phenomenon of material removal is known as the ECDM process. Hole drilling was the first application of ECDM. In order to micro drill glass more precisely, many physical and chemical mechanisms of this process have been studied. In addition to application in the micro hole drilling, fabrication of some 2D and even 3D structures has also been attempted. The first 3D micro-structuring experiment of glass was performed using different types of actuators. In order to obtain a precise machining performance, many studies have been reported on the effects of the working distance and machining voltage, on the influences of machining performance by changing material compositions. Travelling wire electrochemical spark machining (TW-ECSM) generally employs a continuously travelling wire electrode to slice the workpiece by generating spark between wire electrode and electrolyte and keeping electrically non-conducting workpiece in the closed vicinity of the spark. The material of the workpiece is melted, vaporized and eroded due to the transmission of spark energy to the workpiece.

II. Mechanism of material removal

It consists of a traveling wire tool electrode (cathode) and an auxiliary electrode (anode). Work material is immersed up to few millimeters in electrolyte while the auxiliary electrode is kept few centimeters away from the tool electrode. Voltage across the two electrodes is supplied using regulated DC power supply. Cathode wire is slowly displaced. Therefore, renewal of the tool keeps taking place continuously. At lower voltage (below critical voltage), the hydrogen bubbles start to evolve around the tool wire electrode owing to the electrolysis process. Hydrogen bubbles form an insulating layer around the tool electrode. At higher voltages (above critical voltage), when this insulating gas film breaks down it generates sparks discharging from the tool electrode. Thermal energy imparted by spark discharges removes the material from work surface by melting and vaporization

III. 3. Literature Review

3.1. Review on Pyrex glass –

Yang et. Al. [1] added SiC abrasive to the electrolyte, discussed its effects on expansion, roughness and material removal rate (MRR). The experimental results reveal that adding abrasive reduces the slit expansion because it increases the critical voltage. The formation of electrolyte also influences the expansion of the slit, which is smaller in the KOH electrolyte than in the NaOH. The generation of bubbles is more violent in the KOH electrolyte and makes the formation of the dense bubble layer hard difficult. Less discharge energy is released during machining, so the molten area is thinner in the KOH electrolyte. The roughness is significantly improved by adding a smaller abrasive to the electrolyte, which reduces the roughness by 43%. Increasing the concentration and reducing the grit sizes improves the roughness. The abrasive is involved in the machining and helps to refine the micro-cracks and the melted zone formed by discharge heat erosion. In the pure electrolyte, the surface is full of discharge cracks; in the electrolyte to which abrasive has been added, the cracks are shallow. The quality of the slit can be well controlled under suitable conditions (KOH with 300 g/L SiC, #200,100 Hz, DF 0.25). The expansion and the surface roughness of the slit are 0.024mm and 0.84um Ra, respectively.

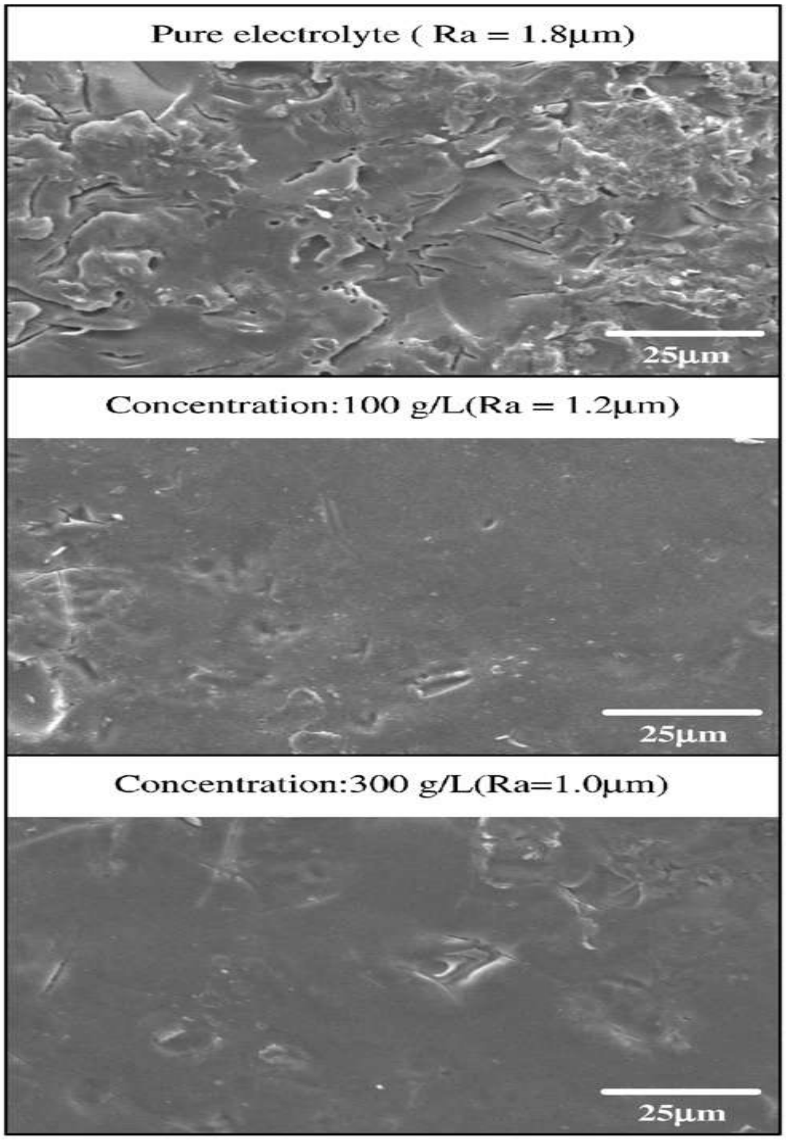

Fig. 1 SEM micrographs of surface at different abrasive concentrations. [1]

Kim et al. [2] worked on Pyrex glass took Electrolyte: KOH: 25%, Electrode: Cu, Graphite, Current: 10 (A) shows the rms roughness, Rq, of the surface micro drilled with the Cu tool. The surface roughness increases as the duty ratio increases and the voltage pulse frequency decreases. The micro drilled surface gets rougher as the thermal damage in the HAZ increases. It is thought that the discharge heat value is greater for long, slow pulses because the duration of the discharge increases. As a result, the micro drilled surface roughness increases, as the HAZ grows larger. By experimental results revealed that, the HAZ can be reduced by decreasing the duty ratio and increasing the pulse frequency of the applied voltage, although the amount of time required to drill the hole will increase because the removal rate decreases.

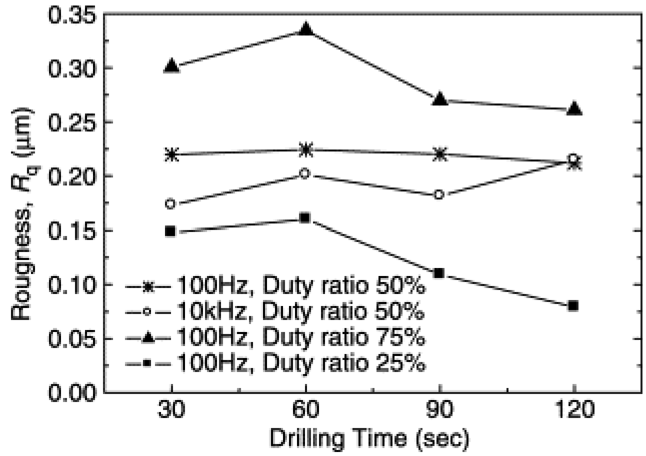

Fig. 2. Surface roughness, *R*q, as a function of micro drilling time. [2]

Bhuyan et. al.[3] worked on Pyrex glass workpiece using L27 orthogonal array considering applied voltage, pulse on-time, pulse off-time, electrolyte concentration and wire feed velocity as input parameters and material removal rate, surface roughness (Ra) and kerf width (Kw) as output parameters. The optimal process parameter setting demonstrates the enhancement of material removal rate by 154% and reduction of surface roughness and kerf width by 21% and 11%, respectively, against the initial parameter setting. The optimum levels of different input process parameters for maximum MRR and minimum Ra as well as Kw obtained are applied voltage at level 2 (75 V), pulse on time at level 3 (500 ms), pulse off-time at level 3 (450ms), electrolyte concentration at level 2 (250 g/L) and wire feed velocity at level 2 (2.4 m/min).It has been found that the pulse off time has least effect on MRR, Ra and Kw compared to other process parameters. For achieving low value of Kw, a higher value of electrolyte concentration is required. It has been observed from ANOVA table that the most important controllable input parameters significantly affecting the multi-performance characteristics of TW-ECSM process are wire feed velocity (40.48%), applied voltage (28.70%), electrolyte concentration (15.42%), pulse on-time (9.06%) and pulse off-time (6.34%).Initial value of surface roughness was 10.2 micron and after optimum design the value of surface roughness reduced to 8.4micron .

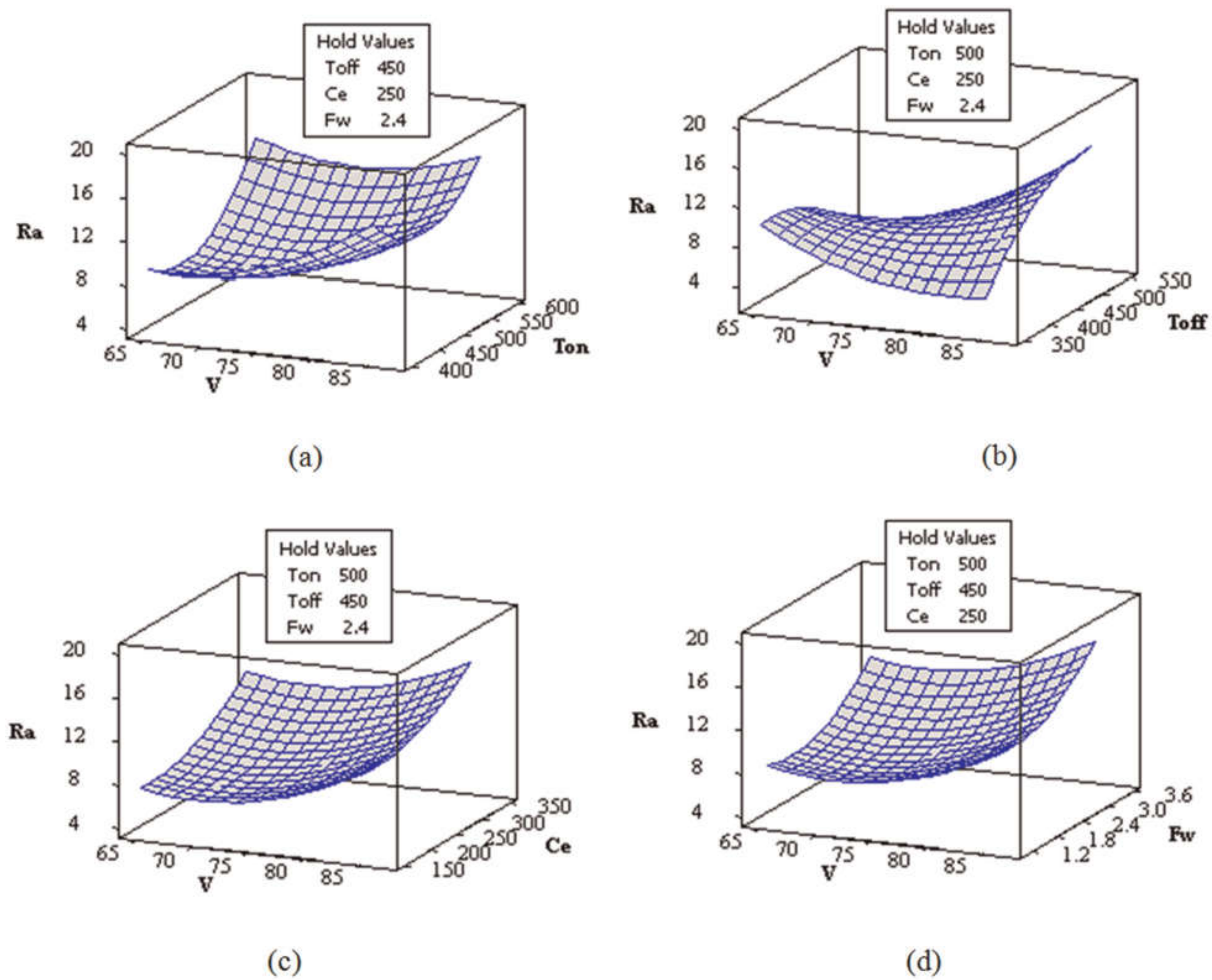

Figure 3. Response surface plot of Ra with (a) applied voltage (V) and pulse on-time (Ton), (b) applied voltage (V) and pulse off-time(Toff), (c) applied voltage (V), electrolyte concentration (Ce), (d) applied voltage (V), and wire feed velocity (Fw).[3]

Jawalker et.al. [4] Mentioned the work done on Pyrex and other glasses by different researchers and mentioned the micromachining process, did micro channeling on soda lime glass using ECDM. Tool Wear (TW) and Material Removal (MR) were studied using design of experiments and L–4 orthogonal array. Experimental results showed that the applied voltage was the most influencing parameter in both MR and TW studies. Field emission scanning electron microscopy (FESEM) results obtained on the micro channel confirmed the presence of micro-cracks, primarily responsible for MR. Chemical etching was also seen along the edges. The Energy dispersive spectroscopy (EDS) results were used to detect the elements present in the debris and specimens. The applied voltage was found to be the most influencing parameter. The FESEM results give useful inputs on failure modes. Small composition of Fe was seen as a result of tool-wear.

3.2 Origin of WECDM

Its first development date back to 1950s in Japan with some applications in diamond die workshops but reported for the first time in 1968 by Kurafuji and Suda[5].and termed it as electrochemical drilling. The possibility of drilling micro holes in glass was demonstrated by them and also studied the electrolyte chemical composition and tool material effect Crichton and McGough [6]., (1985) have concluded that electrolytic gas generated at both electrode surfaces and formation of oxide film on anode surface is responsible for discharge between tool and electrolyte interface with the help of streak photography Tsuchiya et al. [7]. Gave new variant of this process by replacing the tool electrode by wire and named it as wire electrochemical discharge machining (WECDM) and used for cutting glass and other ceramics Jain et al. [8]. In 1991 named it as traveling wire electrochemical spark machining (TW-ECDM) and studied effects of voltage and concentration on MRR, overcut and wire erosion ratio while cutting glass epoxy and Kevlar epoxy composites .Various researchers have presented different views on spark generation, gas film formation, MRR and so on. According to Ghosh [9], switching phenomenon caused spark generation and he determined inductance as an important parameter by enhancing MRR by introducing artificial inductance in ECDM circuit. Jlali[10] et al. presented a hybrid model as local heating proceeded by chemical etching for material removal mechanism. Jain et al. [11]. Have applied successfully valve theory for modeling the discharge phenomenon

3.3 TWECDM Review.

Kuo. et. Al[12] Investigated the application of WECDM with titrated electrolyte flow to processing quartz glass. Proper control of the electrolyte flow rate can ensure both machining efficiency and quality. Maintaining an appropriate discharge gap of 20 μm between the wire electrode and the quartz glass can prevent cramming and ensure the gas film to remain intact, providing reliable insulation. The most appropriate machining parameters for achieving best WECDM performance are the applied voltage of 36V,the electrolyte flow rate of 4.5ml/min and the feed rate of 350 μm/min. WECDM with titrated electrolyte flow has shown good machining performance and yielded good surface quality. In addition, supplying electrolyte in droplets reduces consumption of electrolyte in the processing, thus incurring less cost and pollution.

Rattan et. al.)[13]Used magnetic field-assisted approach for the improvement of TW-ECSM performance, which increases the electrolyte flow, used in the travelling wire (TW)-ECSM process. The experimental results revealed that the MRR increased in the presence of a magnetic field as compared to machining under no magnetic field, with the improvement factor ranging from 9.09% to 200% under different processing conditions. The discharge current was also reduced by the application of magnetic field in the machining process.

Rattan et. al.[14] used a brass wire with diameter 0.1 mm has been used during TW-ECSM process for the very first time The MRR increased with increased values of the supply voltage, electrolyte concentration (%) and wire feed rate during experimentation. The improvement in MRR with magnetic field was found in the percentage range of 9% to

200% during experimentation. from the experimental results that MRR values were found to be more with magnetic field (0.08 to 0.38 mg/min) when compared with no magnetic field MRR values (0.05 to 0.34 mg/min).The machined surfaces with MF-TWECSM process were having less overcut and less HAZ formation problems as compared to the machined surfaces produced by no MF-TWECSM process. After using the regression model, the optimal value obtained for material removal rate and surface roughness was 0.50 mg/min and 9.60 µm respectively

Jain et. al. [15] used NaOH as an electrolyte and found higher machining accuracy is obtained at lower values of voltage and electrolyte concentration. Thermo mechanical phenomenon has been identified as the main mechanism responsible for material removal in TW-ECSM. There is an increase in MRR at higher voltage along with the presence of thermal cracks, large heat affected zone and irregular machined surfaces. For higher machining efficiency, the distance between the anode and the cathode, and the distance between the tool and the work needs to be optimized. Also a minimum distance between the point of power supply and the point of contact of wire with the workpiece is expected to improve the process performance.

Hofy et al. [16] worked Mild Steel, tool-Copper wire (1.5 mm dia.) and NaNO3 as electrolyte, Recommended co-axial flow of electrolyte over perpendicular flow. Reported voltage and feed rate as significant input parameters for higher MRR. Reported on the significance of bubble size around the cathode for electrical spark generation and

Peng et al.[17] machined Quartz using Stainless Steel(0.25 mm dia.) wire and NaOH (5 Molar), KOH(6 Molar) as electrolyte and Categorized current pulse into two modes. A stronger pulse mode that shows better machining results for harder materials like engineering ceramics. Proposed multi step input voltage regulation to improve the current pulse. Reported that wire breakage tends to occur if the duty factor is larger than 0.4.

JW Liu et al.[18] machined Particulate Reinforced Aluminum 6061 using Molybdenum(0.18 mm dia.) wire, Water-based emulsion with NaNO3 (0.03-0.12 M) was used as electrolyte . Used extremely high speed travelling Molybdenum wire at 8 m/s speed and stated that Water-based emulsion along with NaNO3 has 20-500 times conductivity than usual electrolytes used in TWECDM process. This ensures that EDM dominates during the process.

Wang J. et. al. [19] cut Glass with Diamond (0.2 mm dia.) wire and NaCl (3.4 Molar) as electrolyte. Electrolyte spraying was used to provide continuous electrolyte flushing. Reported that WECDM process with abrasive coated wire has limited industrial use. Reported that ECD can be generated with diamond wire. Reported a moderate increase in MRR with a slight increase in Surface roughness during WECDM with diamond wire in comparison with diamond wire sawing.

Kumar et al. [20] worked on epoxy glass, used one parameter at a time (OPAT) technique while conducting their experiments for cutting epoxy glass with TW-ECDM set up and concluded that material removal rate increases with voltage, duty factor, electrolyte concentration and with wire velocity

Dhiman et al. [21] have reported that the toxic fumes produced during machining leads to partial suffocation

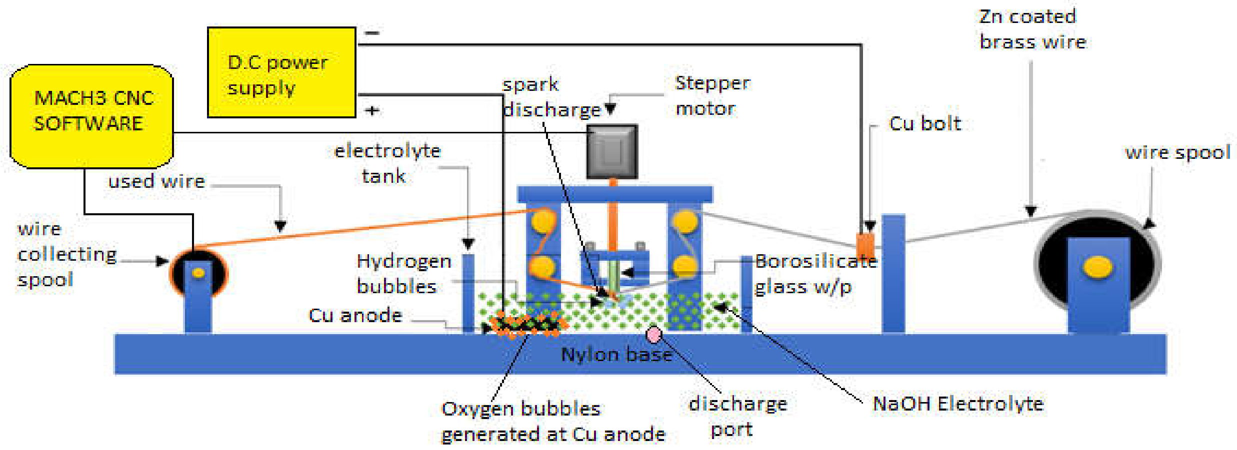

Fig 4 WECDM setup [22]

Kumar M. et. Al. [23] used zinc-layered brass wire during the machining of hard and brittle quartz material and concluded that Layered wire provides better machining characteristics in terms of surface roughness and material removal rate. Also, it improves the machining performance by reducing the wire breakage. SEM images showed the regular and smooth surface obtained at the lower levels of input parameters compared to higher-end levels. At a higher level, shallow cracks with slight necking at the beginning of the machined surface and higher length cuts were observed. For a lower surface finish, voltage and electrolyte concentration are the most significant factors. An ANOVA result revealed that voltage and electrolyte concentration contributions are 92.18% and 4.72% respectively.

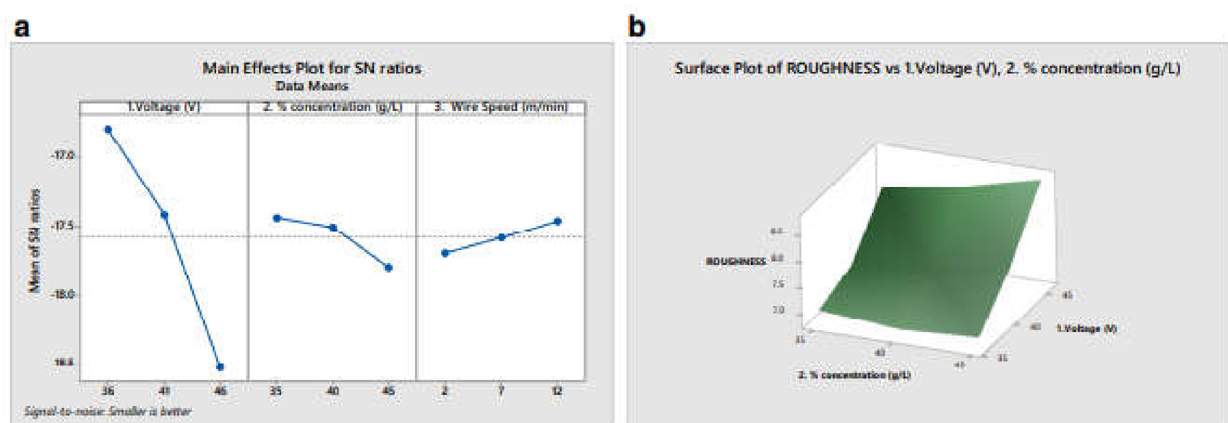

Fig. 5 (a) Main effect plot for SR(Ra). (b) Surface plot for SR(Ra)[23]

IV. Research Gap & FUTURE SCOPE

Pyrex glass has huge range of applications. Despite of huge number of applications very less work has been done on micromachining of Pyrex glass. Research on TWECDM of Pyrex is very limited. Even after decades of study on the process, it is in laboratory stage only and not available for large commercial purposes. Research on TWECDM to reduce thermal cracks and heat affected zones is very limited. There is no dedicated research on wire breakage preventing parameters, the influences of the process parameters, surface roughness. Hence it is very difficult to predict the outcome of the process precisely, literatures are not sufficient in these areas. Only a few of researchers have worked on Pyrex glass. Since Pyrex glass have many physical and chemical properties more work needed to be done on these materials like improvement of surface roughness, splitting Pyrex into two pieces. TWECDM setup should be used for making wafers of Pyrex glass. And work should be done to improve its surface roughness by varying input parameters like voltage, interelectrode gap, electrolyte concentration etc. Magnetic field assisted TWECDM has shown promising scope by improving circulation of electrolyte in narrow gaps

V. Conclusion

Pyrex glass has a huge range of applications such as micro optics, mechanical inertial sensors, micro-pumps, micro fluidic devices, biochip device, biomedical engineering, laboratory on a chip application, DNA sequencers, micro chamber array chip etc. In this paper work done by different researchers on Pyrex glass Micromachining is mentioned. TWECDM can be used for machining Pyrex glass. Experiments done by various researchers on TWECDM setup are also mentioned in this paper. The performance of the process, surface roughness depends on many parameters like tool-electrode material, electrode size and shape, wettability characteristic of tool-electrode, feed-rate, work-piece material, applied voltage, current, duty cycle, pulse duration, electrolyte, its concentration and temperature, gap between tool-electrode and workpiece, distance between cathode and anode, anode material etc. Most frequently used electrolytes are NaOH and KOH as they are less hazardous. There are number of methods being proposed for improvement of TWECDM process. Using abrasive mixed electrolyte, selection of wire, supply of electrolyte etc.

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