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# Experimental Investigations of Traveling Wire Electro-Chemical Spark Machining (TW-ECSM) of Borosilicate Glass

**Basanta Kumar Bhuyan and Vinod Yadava**
Department of Mechanical Engineering,
Motilal Nehru National Institute of Technology,
Allahabad – 211 004, Uttar Pradesh, India
E-mail: bkbhuyan@mnnit.ac.in, vinody@mnnit.ac.in

***Abstract*** **- Traveling Wire Electro-Chemical Spark Machining (TW-ECSM) is an innovative hybrid machining process, combining the features of the Electro Chemical Machining (ECM) and Wire-Electro Discharge Machining (WEDM). It is more suitable for machining of electrically non-conductive engineering materials. Conventional machining methods and some unconventional machining methods cannot be effectively applied for machining of borosilicate glass due to the resulting problems of air borne dust, tool wear and thermal damage. In this paper an inhouse TW-ECSM setup has been designed and fabricated successfully and employed for experimentation. The results about the feasibility of the process and its performance during machining of borosilicate glass have been illustrated. Borosilicate glass, which is frequently used as a material for fabrication of micro structures, was used as a workpiece. Experiments were carried out to investigate the effects of specimen thickness along with different type of wires on material removal rate (MRR). For same set of input parameters, material removal rate is found to decrease initially but after achieving certain value, it begins to increase with increase in specimen thickness.**

***Keywords:*** **Traveling Wire Electro-Chemical Spark Machining (TW-ECSM), Borosilicate Glass, Hybrid Machining Process, MRR**

## 1. INTRODUCTION

Borosilicate is a more stable form of glass, and undergoes less expansion and contraction with changes in atmospheric temperature and pressure. It transmits and reflects a wide range of the light spectrum. For that reason, it is useful in telescopes and optical instruments used in space. It can be ground into a great variety of useful shapes, ground to a high gloss, and coated with useful industrial and scientific materials. It has also been formed into a variety of utilitarian household objects, such as towel rods, coffeepots and light fixtures, as well as jewelry and accessories. Borosilicate glasses are also found in semiconductor application in the micro electro-mechanical systems development.

New ways of cutting hard and brittle non-conductive engineering materials which are difficult-to-machine by conventional methods continue to attract attention. While electrical methods such as electro chemical machining (ECM) and electro discharge machining (EDM) have proved useful, drawbacks such as the expense of tooling for forming large cavities and low rate of material removal have hindered their wider acceptance. Ultrasonic machining (USM), abrasive jet machining (AJM), laser beam machining (LBM), and electron beam machining (EBM) are some of the advanced machining processes that can be used for literature by different researchers, such as Electro chemical arc machining, Electro chemical discharge machining and Spark assisted chemical engraving [3]. The diversity of name illustrates the complexity of the process.

Machining these materials, but dimensional accuracy and surface quality of the machined surfaces are the major concern. Recently, a new trend has been introduced to combine the features of different machining processes. Such machining processes are called as hybrid machining processes (HMPs). HMPs are developed to exploit the advantages of each of the constituent machining processes and diminish the advantages of each constituent process. It has been observed that sometimes, hybrid machining process enhances the material removal rate (MRR), increases the capabilities of the constituent processes, and widen the area of application of the constituent processes. HMPs also reduce some adverse effects of the constituent processes when they are applied individually. Electro-chemical spark machining (ECSM) is one of the HMPs, which combines the features of electro chemical machining and electro discharge machining, has stemmed from its ability to remove metal at high rates, as much as five and fifty times faster than ECM and EDM, respectively under the same parameter setting [1]. The ECSM process uses Electro-Chemical Discharge (ECD) phenomenon for generating heat for the purpose of removing work material by melting and vaporization. This was presented for the first time in 1968 by Kurafuji as “Electro-chemical Discharge Drilling” for microholes in glass [2]. Several other names of ECSM are used in ECSM with ECD have been tried in many configurations: Die Sinking-ECSM, Hole Sinking-ECSM, Die Drilling-ECSM, Hole Drilling-ECSM, Wire Cutting-ECSM, Disc Cutting-ECSM, Cylindrical Grinding-ECSM, Surface Grinding-ECSM and Pocket Milling-ECSM. Die Sinking–ECSM operation usually involves machining of cavity using non-rotating tool electrode, where as in hole drilling–ECSM a rotating tool electrode is used with the main focus on the surface quality of side wall of the hole. Wire cutting–ECSM is capable of slicing large volumes and machining complex shapes of non-conducting materials without the need of full form tool electrode. In contour milling–ECSM, a simple shape tool electrode is used to produce a three-dimensional (3-D) cavity by adapting a movement strategy similar to conventional milling. Success in the application of sinking and drilling ECSM has stimulated interest in studying the prospects of TW-ECSM. The development of the Traveling Wire Electro-Chemical Spark Machining (TW–ECSM) is the outcome of machining requirements. In 1985, Tsuchiya *et al*. [4] proposed TW-ECSM first time for cutting non-conducting materials such as glasses and ceramics. Various researchers have put forth explanations of ECD phenomenon based on their experimental studies.

Bhattacharya *et al*. [5] conducted experiments on alumina and concluded that the most effective parametric combination for moderately higher machining rate and dimensional accuracy are 80V and 25% NaOH concentration. Tool tip geometry was also found to play an important role in a controlled spark generation in ECDM. Kulkarni *et al*. [6] proposed the discharge phenomenon similar to arc discharge in gases. They proposed that hydrogen gas bubbles get accumulated at the tool-electrode tip leading to combining of bubbles into a single large bubble which isolates the tip completely from the electrolyte. This causes the local electric field gradient between the tool and electrolyte interface to go beyond the breakdown limit of 25V/μm leading to an arc discharge. Basak and Ghosh [7] treated the discharge phenomenon as a switching off process due to bubble bridges. Hofy and McGeough [1] carried out experimental studies on the effects of mode of electrolyte flushing, wire erosion, machining speed on metal removal rate during TW-ECAM. Their recommendation was to use coaxial mode of flushing for maintaining the machining action and its accuracy and also reported the values of bubble diameters, 1μm.

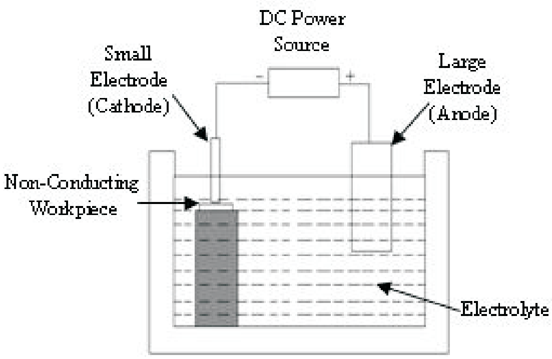
Peng and Liao [8] verified that TW-ECDM can be applied for slicing meso-size non-conductive brittle materials of several millimeters thick. They have shown that pulsed DC power shows better spark stability and more spark energy than constant DC power. Nesarikar *et al*. [9] carried out experimental study for the feasibility of TW-ECSM process for precision slicing of thick Kevlar-epoxy composite. They did comparison between the experimental and calculated values of MRR and average diametral overcut with the variations in electrolyte conductivity, applied voltage and specimen thickness. Jain *et al*. [10] carried out experiments on their self developed setup of TW-ECSM for cutting Glass epoxy and Kevlar epoxy composites using NaOH electrolyte. They found that the wire wear rate and the overcut follow a similar behavior as the machining rate but the wire wear rate is about two magnitudes smaller than the MRR. They also tried to study the effect of artificially introducing some bubbles into the process during machining and found that the MRR as well as the overcut decreases slightly. Yang *et al*. [11] carried out experimental study to improve the overcut quality by adding SiC abrasive to the electrolyte. They discussed the effects of abrasive on expansion, roughness and MRR on the various machining parameters in Wire Electro-Chemical Discharge Machining (WECDM). Singh *et al*. [12] attempted to explore the feasibility of using TW-ECSM process for machining of electrically partially conductive materials like lead zirconate titanate and carbon fiber epoxy composites. They found that MRR increases with increase in supply voltage. MRR also increases with increase in concentration of the electrolyte up to around 20 wt. %. Beyond this concentration, it starts decreasing. They also observed that machined surface shows evidence of melting. Large cracks are sometimes observed when the machining is done at higher voltage. However, such cracking is not seen at lower voltage.

Based on the above literature survey, studied in depth, it has been found that the ECSM process in general and the TW-ECSM process in particular has not been commercialized and literature available for this process is still scarce. The focus of the present work is on developing an inhouse TW-ECSM setup and experimental analysis of the non-conducting engineering materials. The effects of specimen thickness and type of wires on material removal rate have also been observed.

## II. Fundamental of ECSM

The ECSM process involves a complex combination of the electro chemical action and electro discharge action.

The electrochemical action helps in the generation of the positively charged ionic gas bubbles, i.e. hydrogen gas ($H_2$). The electro discharge action takes place between tool and workpiece due to breakdown of the insulating layer of the gas bubbles. In ECSM process, an electrochemical cell consists of two electrodes dipped in electrolyte, one is larger electrode (anode) called as dummy electrode or auxiliary electrode and another one is smaller electrode (cathode). The distance between two electrodes is 30-50 mm and smaller size electrode is dipped 2-3 mm below the electrolyte as shown in Fig. 1.



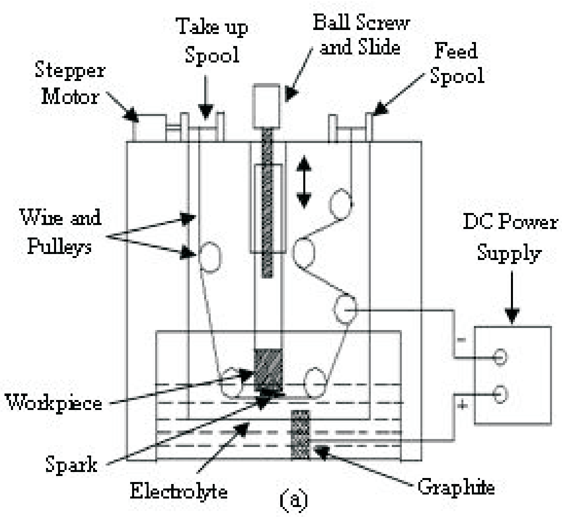



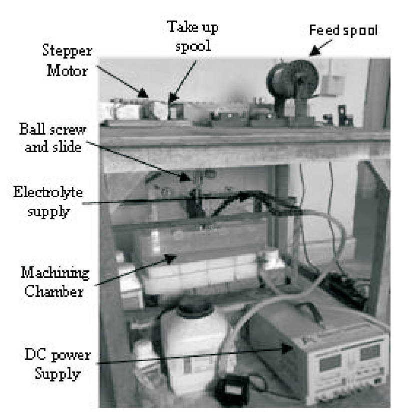

Fig. 1 Electro-Chemical cell with two electrodes of grossly different size

When an external potential is applied between the electrodes, electrical current flows through a cell resulting in electrochemical reactions such as anodic dissolution, cathodic deposition, electrolysis of electrolyte etc. Surface area of the cathode dipped in the electrolyte is very small compared to anode hence high current density at the cathode results in rapid generation of hydrogen gas bubbles and oxygen gas bubbles at the anode due to electrochemical reactions. Boiling of electrolyte near small electrode would occur due to Ohmic heating of the electrolyte. Beyond a certain value of the applied potential, electric sparks appear at the smaller electrode and the cell current drops. This is known as Electro-Chemical Discharge (ECD) phenomenon [2]. There are various theories [3] proposed to explain the mechanism of spark generation at the cathode. However, none of them has been verified experimentally.

In TW-ECSM process, D.C power is supplied between the wire and the auxiliary electrode and the sparking takes place between the wire and electrolyte and hydrogen gas bubbles are accumulated and insulating layer is formed near the wire surface. With the further increase of applied voltage, sparking from wire takes place. If the workpiece is kept in the vicinity of the spark zone, material is removed by melting and vaporization. Thus the material removal process in traveling wire electrochemical spark machining is very complex in nature which is governed by various process parameters. The experimental setup of TW-ECSM has to be developed so that the process parameters are to be properly controlled to achieve the good machining performance.

### III. Developed Experimental TW-ECSM Setup

Traveling Wire Electro-Chemical Spark Machining (TW-ECSM) setup has been designed and fabricated keeping in view the fundamental mechanism of the process and basic functional requirements of different parts. The setup was performed after assembling various indigenously developed basic components such as, Machining chamber, Wire driving system, Electrolyte supply system and Power supply system. A schematic diagram of the Traveling Wire ECSM setup is shown in Fig. 2 (a) and a photograph of the setup is also shown in Fig. 2 (b).




(b)

Fig. 2 (a) Schematic diagram of TW-ECSM setup and (b) Photographic view of the developed tabletop TW-ECSM setup

The machining chamber of size 400mmx250mm x110mm is made of Plexiglass holds the electrolyte, as it is an electrically insulating, transparent and corrosion resistant material. It is kept on the lower platform of a wooden table. On the middle wall of the machining chamber electrode positioning and job-feeding unit is fixed. At the bottom of machining chamber a hole is provided to drain out electrolyte from chamber. Within machining chamber the tool electrode is just touching the non-conducting workpiece such as borosilicate glass. The auxiliary electrode is a vertical graphite rod and a horizontal scale is attached at the centre of the top edge of the vertical rod. The horizontal scale is provided in order to measure the horizontal displacement of the auxiliary electrode which in turn helps to measure and control the inter electrode gap. In the base and side wall of the machining chamber, pulleys are attached, which helps in movement of wire throughout machining chamber. The electrolyte reservoir is attached with the side wall of the machining chamber in order to supply electrolyte. The workpiece holder is made of iron plate. A vertical up and down movement up to 30mm can be made to change the depth of the workpiece in the electrolyte by using depth control mechanism.

The wire driving system consists of a feed spool, a take-up spool, a set of pulleys and a stepper motor. The step angle of the stepper motor is 1.8º. The rpm of the stepper motor can be varied from 1 to 80. The programmable Logic Controller (PLC) is used to rotate the stepper motor smoothly. The input voltage to the stepper motor is 24V and the input current to the stepper motor is 2.8A. The torque of the stepper motor is 20kgcm. The wire electrode is fed towards the workpiece at a constant rate from a feed spool through a set of pulleys to the take-up spool. The pulley that is submerged in the electrolyte is made of Teflon and other pulleys are made of copper. A stepper motor drives the take-up spool to pull the wire gently at a constant speed. An anode made of graphite is attached to the pulley mount and its distance from the cathode (wire) can be adjusted. The distance between two electrodes is 30-50mm from each other.

The electrolyte supply system consists of a pump and a flow control valve. The electrolyte is supplied to the cutting site on the work specimen can be immersed thoroughly in the electrolyte. There are two different modes of electrolyte flushing, such as (a) electrolyte flushing perpendicular to wire and (b) electrolyte flushing coaxial with wire. The electrolyte is added to the machining chamber from the reservoir in the form of drops instead of flow from pipe. If electrolyte is fed with high velocity, there will be no formation of insulating layer or gas bubbles. Hence for this thermal consideration the electrolyte should be added drop by drop.

The power supply system used in TW-ECSM is mostly DC power supply voltage able to maintain about 40V across the cathodic tool-electrode and anodic auxiliary electrode. Pulsating current can be applied to increase the performance of TW-ECSM. Pulsating current has three parameters such as pulse on-time, pulse off time and peak current density. In the pulsed TW-ECSM process, a pulse generator is used to supply the voltage pulses across the electrodes. Pulsing is applied to this D.C by means of a timer control. The main 230 volts, 3 phases, AC power supply are converted to low voltage D.C power supply by a step down transformer and silicon controlled rectifier unit. The positive terminal of the power supply unit is connected with auxiliary electrode and one end of the coil heating the electrolyte. The negative terminal of the power supply unit is connected with wire and another end of heating coil. Thus temperature of the electrolyte is controlled electrically from 20°C to 60°C. The voltage and current can be recorded with a voltmeter and ammeter.

## IV. Experimentation

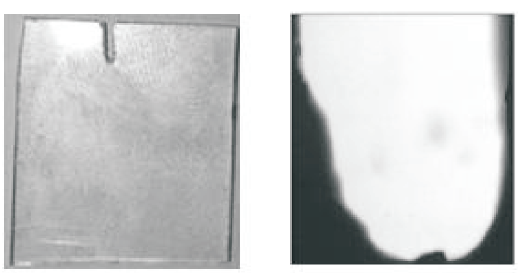
Experiments of TW-ECSM have been conducted by varying specimen thickness, keeping other parameters constant. Initial experiments were performed in borosilicate glass with graphite rod (diameter 8mm, length 55mm) as anode and copper wire of diameter 0.70mm, brass wire of diameter 0.25mm and stainless steel of diameter 0.50mm as cathode. A rectangular borosilicate glass of size 40mm×35mm×2mm was adopted as a workpiece. Workpiece was held at constant distance of about 35mm from the anode. Cathode (wire) was always kept in physical contact with the workpiece which was mounted on the supporting platform. Copper wire and stainless steel wire were broken frequently even at 64 volts but brass wire was broken at 50 volts because of its low current carrying capacity. Very low wire speed would lead to the situation similar to the stationary tool resulting in overheating and finally breaking of the wire. Too high wire speed was also not desirable because it would be uneconomical. Hence, wire was driven by stepper motor at a constant speed of 1.2 m/min. An aqueous solution of NaOH with a 200g/l solution at 20ºC, was used.

NaOH has higher specific conductance, reactions take place at higher rates, so a larger amount of gases were evolved. Hence, higher MRR was achieved. Therefore, all the experiments reported in this paper were carried out using NaOH solution as electrolyte. Each experiment was tested for about 5 to 12 min, during which voltage and current were recorded on a voltmeter and ammeter, respectively. The minimum linear feed rate to the workpiece which could be achieved using the present setup was 0.008mm/s. This feed rate was higher than the cutting rate observed during the experiments. The nature of graph observed that MRR of borosilicate glass using copper wire and stainless steel are greater than the MRR using brass wire of same material, keeping other parameter constant. This is because of copper wire is a more electrically conductive than brass wire and as per the diameter concerned, stainless steel wire diameter was greater than brass wire diameter. Copper possesses excellent conductivity rating, low tensile strength, high melting point and low vapour pressure rating which severely limited potential. As new materials and demands came, developers subsequently experimented with the use of brass in order to meet the new demands. Brass is an alloy of copper and zinc. Generally, the higher the zinc percentage, the better the wire is for EDM.

## V. Results And Discussion

### *A. Machining of Borosilicate Glass*

Micrograph of the specimen after machining has been studied with the help of Optical Measuring Microscope (OMM) as shown in Fig. 3.



(a) (b)

Fig. 3 Machining of borosilicate glass (a) groove cut and (b) micrograph of groove cut using optical measuring microscope 10X

Fig. 3 (a) shows after slicing of borosilicate glass with keeping other parameter constant and (b) represents the micrographs of machining portion of the specimen by using optical measuring microscope 10X. Initial experiments were performed in borosilicate glass with graphite rod as anode and brass wire of diameter 0.25mm as cathode. Likewise, other experiments were performed. Each experiment was tested about 5 to 12 minutes, during which time the machining of current and voltage were recorded as ammeter and voltmeter respectively. Brass is an excellent thermal and electrical conductive material as well as less corrosive. So that current rises at the machining of the materials within less time, results more hydrogen bubbles accumulate at the tool tip and more material removes.

### *B. Material Removal Rate*

After machining, the workpiece was washed, dried to evaporate any water remaining on the surface and reweighed using a weighing digital micro balance (accuracy 10µg, CAS India Private Limited). The difference between the original weight and the final weight gave the amount of material removed. In this work, material removal rate in millimeter per minute was evaluated as shown in Fig. 4. The efficiency of the machining process is also usually evaluated in terms of material removal rate in milligrams per second.

### *1. Effect of Specimen Thickness*

The effect of specimen thickness on MRR for borosilicate glass with considering copper wire, stainless steel and brass wire as shown in Fig. 4. MRR is decreasing with increase in specimen thickness in the first part of the curves. This is because of the obstruction in the current path resulting in less bubble formation on the wire passing through the groove and the energy generated on the wire away from the workpiece is wasted in heating the electrolyte. Similarly, second part of the curve, MRR increases with increase in specimen thickness. This is due to the discharge zone in the vicinity of the wire gets shifted to the top of the workpiece and more bubble concentration on the wire passing through the groove.

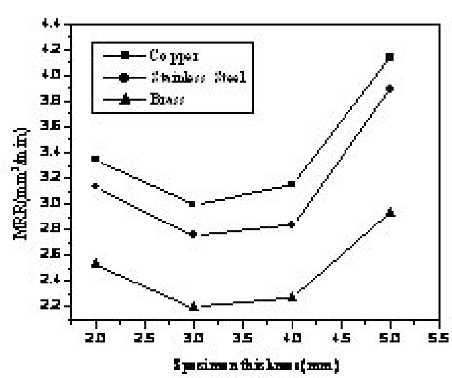



Fig. 4 Effect of specimen thickness on MRR

The Fig. 4 also shows that machining of borosilicate glass with brass wire is better than copper and stainless steel wire but low MRR than other two, due to low voltage. We also observed that MRR decreases initially up to 3mm thickness of the specimen and then increases with an increase in the thickness of the specimen.

## VI. Conclusions

Based on the experimentally obtained results during machining of electrically non-conductive borosilicate glass on designed and fabricated TW-ECSM setup and thereafter discussion on the investigated results, the following conclusions are drawn as listed below.

1. It has been found that machining of borosilicate glass with brass wire is better than the copper wire and stainless steel.
2. MRR has been observed to decrease initially with an increase in specimen thickness upto certain value and then increases continuously.

## Acknowledgement

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