International Journal of Technical Innovation in Modern Engineering & Science (IJTIMES)
Impact Factor: 5.22 (SJIF-2017), e-ISSN: 2455-2585
Volume 5, Issue 06, June-2019

A REVIEW ON MICROMACHINING BY WIRE ELECTROCHEMICAL DISCHARGE PHENOMENA

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Abstract*— Micromachining of glass and other non conductive materials have gained importance in recently growing advance engineering and biomedical fields for various applications like MEMS, lab on chip devices, microfludic devices and so on. The difficulty of machining these material by traditional processes led the researchers to develop the alternative process, Electrochemical discharge machining (ECDM) and its variant Wire Electrochemical discharge machining (WECDM) is an advance machining process, can machine such materials with accuracy. The input parameters such as voltage, electrolyte concentration, feed rate etc. govern the process performance parameters like material removal rate, overcut, surface irregularity and surface integrity of machined surface. The process works on the principle of electrochemical discharge, the exact mechanism of machining is not well understood. The paper presents the review past research carried out in WECDM process.

***Keywords*— ECDM, WECDM, surface integrity, voltage, surface roughness, material.**

I. INTRODUCTION

Since the beginning of life of on planet, humanity has invested a lot in processing of materials from early shaping of stones in Stone Age to revolutionary invention of wheel in Bronze Age to eighteenth century industrial revolution. With the time, there has been seen tremendous growth in materials science also. The advent of these ceramics, glass, composites, smart materials, bio materials, etc. having superior properties poses a challenge to researchers for their machining. This gave birth to new field of machining known as non-traditional machining or non-conventional machining processes like water jet machining (WJM), electrochemical machining (ECM), abrasive jet machining (AJM), and electric discharge machining (EDM), laser beam machining (LBM), electron beam machining (EBM) and many more. These processes have their own capabilities and limitations owing to their working principle. But today scenario has changed dramatically from macro-machining to micromachining to produce highly sophisticated intricate and complex micro-components for various fields like aerospace, biomedical, defense and so on. The perspective of manufacturing is changing in the recent times [1].

Apart from other advance materials, glass being chemical resistant, transparent and having low thermal expansion coefficient and high strength to weight ratio has made it more suitable in recently growing advance engineering and biomedical fields for various applications like MEMS, lab on chip devices, micro filters , micro pumps, micro valves, drug delivery devices and so on. Micro fluidic technologies have seen tremendous growth over the last few years. The borosilicate glass serves the substrate of micro devices due to its good surface integrity, acid durability, corrosion and thermal shock resistance. However being hard, brittle and nonconductive in nature it proves a little difficult to machine through conventional processes because of crack propagation, fracture, poor surface texture, cutting through grain boundaries etcetera. Also, developing micro features seems quite cumbersome through conventional processes. Meanwhile non-conventional machining processes required for this but they also have some inherent disadvantages. For example, some non-conventional machining processes like EDM, ECM, and WEDM can't machine non-conductive materials. Other processes like Ultrasonic machining, abrasive jet machining, laser beam machining, ion beam machining can machine electrically non-conductive materials but poor surface finish, inferior dimensional accuracy, inadequate material removal rate and heat-effected zone, etc pushed to look for some other processes which can overlook these problems also.

Interestingly a hybrid non-conventional machining technique called electrochemical discharge machining (ECDM) has emerged as successful tool for cutting these non-conducting and brittle materials. 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 and termed it as electrochemical drilling. It combines the features of both EDM and ECM. It makes use of electrochemical and physical phenomena to machine glass. The basic principle is explained in Fig. 1. The workpiece is dipped in an appropriate electrolytic solution (typically NaOH or KOH). A constant DC voltage is applied between the tool-electrode and the counter-electrode. The tool-electrode is dipped a few millimetres in the electrolytic solution and the counter-electrode is, in general, a large flat plate. The tool-electrode surface is always significantly smaller than the counter-electrode surface (by about a factor of 100). The tool-electrode is generally polarised as a cathode, but the opposite polarisation is also possible

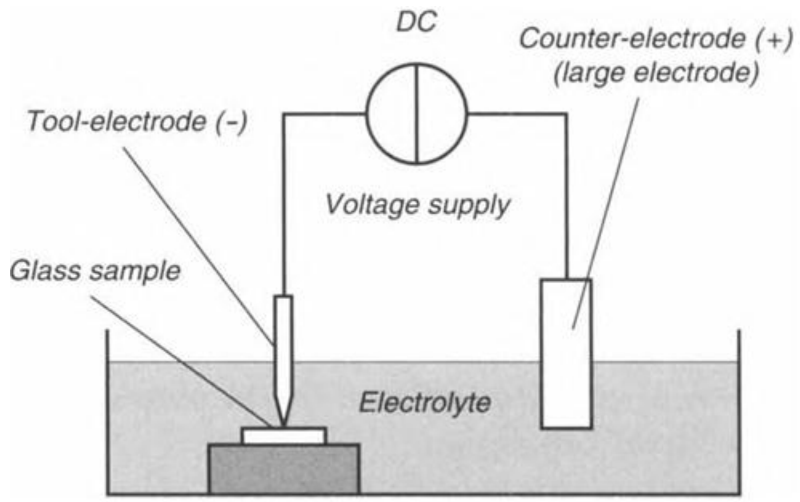

Figure 1 schematic diagram of ECDM set up

When the terminal voltage is lower than critical discharge voltage, electrolysis occurs. Hydrogen bubbles are generated at tool electrode and oxygen bubbles generated at auxiliary electrode. As the current density increases and more and more bubbles are formed and a bubble layer develops around the electrodes. The density of the bubbles and their mean radius increase with increasing current density. When the terminal voltage is increased above the critical voltage, the bubbles coalesce into a gas film around the tool-electrode. Electrochemical discharge occurs between tool electrode and electrolyte when the applied voltage reaches the critical voltage value so material removal takes place from glass due to local heating. The gap between the tool electrode and glass piece should be less than 25 µm. The toxic fumes produced during machining leads to partial suffocation [2].

II. WIRE ELECTROCHEMICAL DISCHARGE MACHINING (WECDM)

A Tsuchiya et al. in 1985 gave new variant of ECDM 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. 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. Since then this process has been exploited by various researchers for micro slicing various non-conducting difficult to machine materials.

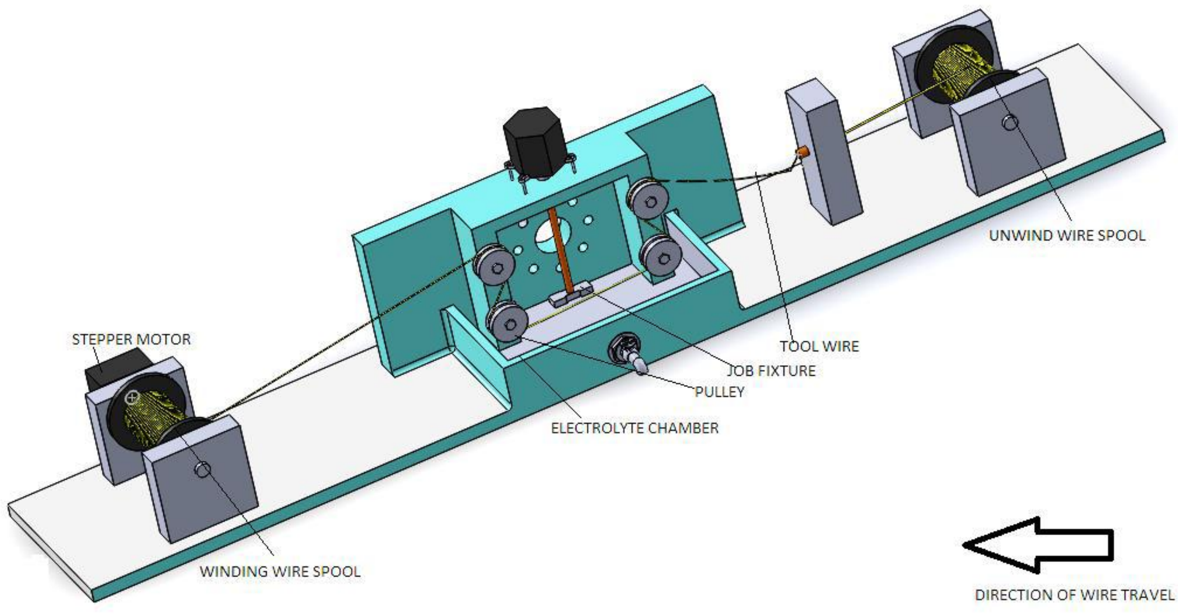

Figure 2 the schematic diagram of TW-ECDM set up

This process is a hybridization of ECM and WEDM utilizing benefits of both the procedures. The setup includes an electrolytic cell or tank which has basic, acidic or salt based electrolyte in it to transfer electricity and to cause chemical reactions. A wire connected with negative of DC source traveling constantly at a certain speed just touches the electrolyte free surface and a cylindrical rod of metal or graphite enormously larger than the wire is connected to the positive of the DC source and is dipped inside the electrolyte. An electrically non-conductive hard and brittle workpiece is placed near the wire electrolyte touching zone. Stepper motor controls the speed of the wire and the feed of the workpiece. DC voltage is applied to the electrodes which initiates electrolysis and causes a spark which in turn helps in slicing the workpiece because of excessive and concentrated heat area the wire becomes too hot and to transfer the heat to the next segment of wire, it has to move at a certain speed. Slow wire movement can cause wire breakage and fast movement can hinder in bubble formation. Proper control of electrolyte level in the electrolyte tank is also very important parameter..

A. PRINCIPLE/MECHANISM

The basic principle of this process is similar to electrochemical discharge machining (ECDM) except tool used in this process is wire of small diameter instead of specialized tool used in ECDM. This process utilizes the energy of discharge to melting the workpiece area in the vicinity of discharge area, thus causing required material removal. TW-ECDM has a wire as cathode and an auxiliary electrode extraordinarily larger in size than the wire as anode. Anode is dipped fully in electrolyte and cathode just touches the electrolyte placed in an electrolyte tank. The electrolyte is used as a working fluid here to complete the electrical circuit between them and also for other purposes like cooling. The voltage supplied depends on electrolyte used and the material of workpiece. The workpiece used in this process is essentially non-conducting, brittle and hard like glass, ceramics, etc which are difficult to machine by other non-conventional processes like EDM, ECM and WEDM. A DC voltage is applied between the electrodes which start the electrolysis process and the formation of H_2 gas bubbles at cathode (wire) and O_2 gas bubbles at anode. When the number of H_2 gas bubbles formed at wire becomes substantial, these coalesce to form an insulating layer around the wire which causes the resistance at wire-electrolyte interface to become huge. This heightened resistance causes more heat which vaporizes the electrolyte causing in turn an electrically non-conducting layer of H_2 and vapor mix layer around the wire. When the applied voltage overcomes this resistance, that is, when it crosses a critical level, discharge of electrons occurs in form of spark at the wire electrolyte interface creating radiation powerful enough to melt the workpiece. Energy of that spark varies proportionally to the applied voltage between the two electrodes. In order to machine the workpiece, it has to be placed in a zone close to the discharge so that spark energy can be utilized to melt, vaporize and erode it.

The movement of these ions towards oppositely charged electrode helps in flow of current and completes the circuit. If a basic electrolyte like NaOH is used, the hydrogen ions (H^+) will come from the water that is used to make the electrolytic solution and the hydroxide ions (OH^-) will come from both the basic electrolyte as well as water.

$H_2O \rightarrow H^+ + OH^-$

$NaOH \rightarrow Na^+ + OH^-$

The chemical reactions which occur with the supply of DC power that evolves hydrogen gas around cathode which in turn helps in the discharge causing the machining are as follows: -

At cathode: $2H_2O + 2e^- \rightarrow H_2\uparrow + 2\,OH^-$

At anode: $4(OH^-) \rightarrow 2\,H_2O + O_2\uparrow + 4e^-$

Various researchers have presented different views on spark generation, gas film formation, MRR and so on. According to Ghosh [3], switching phenomenon caused spark generation and he determined inductance as an important parameter by enhancing MRR by introducing artificial inductance in ECDM circuit. Jlali et al. [4] presented a hybrid model as local heating proceeded by chemical etching for material removal mechanism. Jain [5] has applied successfully valve theory for modeling the discharge phenomenon. Singh [6] claimed that the micro-slots fabricated needs secondary process for their surface finishing.

III. LITERATURE REVIEW

Tsuchiya et al. [7] reported wire electrochemical discharge machining (WECDM) first time in 1985. They derived this new variant of electrochemical discharge machining (ECDM) process by replacing the tool electrode by wire and used the name electrochemical discharge machining (WECDM) for the first time. They used it for cutting glass and other ceramics and discussed the effects of applied voltage, electrolyte concentration on material removal.

Jain et al. [8] gave traveling wire electrochemical spark machining(TW-ECSM) name for this process and used their in-house developed TW-ECSM set up for carrying out experiments are on glass-epoxy and Kevlar-epoxy composites, using sodium hydroxide (NaOH) as electrolyte . The effects of voltage and concentration of the electrolyte on material removal rate, average diametric overcut, tool wear rate, and wire erosion ratio were reported. The theoretical analysis of the mechanism of the process identifies the thermo mechanical phenomena as the main source of material removal in ECSM. They concluded that MRR increases with the increase in voltage because increase in voltage implies higher discharge energy per spark hence higher MRR. Also MRR increases with an increase in electrolyte concentration up to 15 percent and then starts decreasing. They also concluded that similar to MRR, average diametric overcut increases up to 15 percent and then decreases.

Kumar and Yadava [9] investigated TWECDM of epoxy glass using one parameter at a time technique. They used a graphite rod of 8mm in diameter as anode and a brass wire of 0.25 mm diameter as cathode. NaOH was used as an electrolyte with range of 150 g/L to 250 g/L at a temperature of 20^0C to 40^0C. The voltage range was 35-45 V and current range was 0.5-3 A. Wire speed was decided in a range of 1.2 m/min to 2.4 m/min. The time for each trial was 10 minutes. The feed rate of workpiece was ranged between 0.008mm to 0.01mm/s. Pulsating DC power supply was used to perform the experiments as it has better spark stability with pulse on-time ranging between 200 µs-400 µs and pulse off-time ranging between 100 µs to 300 µs. They observed an increase in MRR with voltage accompanied with micro-cracks at higher voltage. Also, MRR increased with increase in electrolytic concentration up to 40% then it started to decrease. They also observed an increase in MRR with proportional duty factor 80%.

Kumar and Yadava [10] used TW-ECDM set up for cutting the borosilicate glass and studied the effects of supply voltage, pulse on-time and electrolyte concentration on the material removal rate (MRR) and surface roughness (Ra). MRR and R_a have been found to increase with an increase in supply voltage. It has also been observed that an increase in MRR at higher voltage and R_a is less at lower voltage. With increase in pulse on-time, there is an increase in material removal rate and surface roughness. It has also been observed that MRR is more at pulse on-time 0.40ms and Ra is less at pulse on-time 0.20ms. MRR also increases with an increase in electrolyte concentration up to around 20 percent. After this it starts decreasing because of higher concentration the specific conductivity of NaOH decreases.

Rattan et al [11] have used a magneto hydrodynamic (MHD) convection process to increase the electrolyte flow in travelling wire electro chemical spark machining process. The experiment was done on quartz material with brass wire of diameter 100 µm taken as cathode and NaOH was used as an electrolyte. Neodymium based permanent magnet was used to apply magnetic field in perpendicular direction to the electric field applied. The application of magnetic field generates a Lorentz force which helps in driving the ions in the electrolyte enhancing circulation by providing stirring and jet effect. At first, the North Pole was put facing the machining area which formed the electrolyte jet in similar direction to the wire feed direction which made the removal of debris easier. MRR improvement ratio was also established and was found to be varying from 9.09% to 200% for various processing conditions. Also, the discharge current reduced to 0.80-1.2A in the presence of a magnetic field instead of 0.85-1.3A when magnetic field was not applied.

Malik et al. [12] used their in-house developed travel wire electrochemical spark machining (WECSM) set up to machine the e-glass fibre epoxy composite that is difficult to machine by any well-known non-conventional machining methods like electrical discharge machining, wire electrical discharge machining, etc. This material can be machined with conventional machining but compromise with accuracy, surface texture, etc. The experiments were carried out to investigate the effect of different parameters of developed WECSM on machining performance characteristics such as material removal and spark gap width. Test results reveled that the width of micro slice varied from 220 to 223 µm when slicing operation was performed with 200 µm diameter brass wire. They found the parameters, electrolyte concentration and DC Supply voltage to be the most significant parameters on material removal with 65.33 and 29.94 % contributions, respectively. They also observed undissolved fibres along the cutting surfaces that may be due to the adhering of small particles scattered from the workpiece surface during cutting. It is due to not flow of electrolyte during machining.

Liu et al. [13] used WECDM set up for cutting of 10 % and 20 % Al2O3 particle-reinforced aluminum alloy 6061 and studied the effect of EDM and ECM actions on MRR using voltage waveforms. They concluded from their experiments that high voltage reduces MRR where as high machining current leads to an increase in MMR and concluded that ECM action is dominant over EDM action at high concentration of electrolyte.

Wang et al. [14] developed oil film-assisted vertical WECDM set up and machined a 10mm thick quartz glass piece and found out that the oil film helps in stabilising insulating film on wire, which facilitates the generation of electrochemical discharges. According to their experimental results, MRR and slit width increases with increase in voltage and the slit width becomes uneven when the applied voltage exceeds 70 V while the increase in electrolyte spraying velocity leads to increase in MRR initially and then decreases but the slit width keeps on increasing. They suggested the wire velocity to be kept with in 0.05 and 0.35 m/s range otherwise MRR will decrease.

Liu et al. [15] used the rotary helical tool as a wire electrode for their developed WECDM set up and found that rotary tool leads to removal of debris and facilitated the refreshment of electrolyte in the micro kerfs machined. They concluded experimentally that the side gap increases with the increase in voltage and duty factor and it reduces with the increase in spindle speed, frequency and feed velocity and proposed that set up using helical tool as a wire electrode can be used effectively for micromachining complex closed pattern structures.

Yang et al. [16] have mixed the SiC abrasives to the electrolyte for enhancing performance of WECDM. They have found that the addition of SiC abrasive particles increases the critical voltage and reduces the discharge energy, thus helps in reducing the discharge energy and also leads to reduction in slit expansion. Also addition of abrasives helps in reducing the surface roughness and smaller grit size results in lower roughness value. Higher power frequency results in improving surface topography.

Kou et al. [17] have used titrated flow of electrolyte for machining of quartz. They have found that fluid inside the droplet results in removing the chips and electrolysis resultants by forming eddies on both sides of workpiece. They have experimentally determined 20µm gap between the wire electrode and workpiece to be the appropriate gap for stable film formation. They have optimized the parameters as 36 V applied voltage, 4.5 ml/min electrolyte flow rate and 350 µm/min feed rate for best WECDM performance and concluded that titrated flow to be efficient and economical.

Bhuyan et al. [18] have used a hybrid methodology comprising of Taguchi methodology (TM) coupled with response surface methodology (RSM) for modeling and TM coupled with weighted principal component (WPC) methodology. Optimized parameter values by TM were used as input values in RSM for developing the second order response model. Input parameters for Ra and MRR were optimized. . They have found that for achieving smaller value of Ra and larger value of MRR a higher value of wire feed velocity is required. The application of TMWPC approach has reduced Ra by 15% and improved MRR by 222% from the initial value. It has been observed that in comparison to TM, the hybrid approach enhances MRR by 46% and reduces the Ra by 10%.

Han et al. [19] used TWECDM employing cylindrical tool with micro-textures on the surface as a cutting electrode for two dimensional contour cutting of soda-lime glass. Partial electrical shielding of the tool electrode was also used to stabilize the discharge characteristics by minimizing the reactive tool area. They have found that WECDM process using traveling wire suffers from low surface integrity because of the high working voltage and long reactive tool length compared to those of the micro-ECDM process. Improved surface integrity using cylindrical tool method was experimentally verified by cutting soda-lime glass with a thickness of 0.4 mm. The lowest R_a among the machined surfaces was 0.3 mm, obtained with a working voltage of 28 volts, a reactive tool length of 1.0 mm, and a tool feed rate of 90 mm/min.

Oza et al. [20] have used traveling wire electrochemical discharge machining (TW-ECDM) process for machining of quartz ceramics. Taguchi robust design was performed to identify the optimal parametric conditions using L9 orthogonal array. Signal to noise (S/N) ratio and ANOVA were used to optimize the parameters. Zinc coated brass wire with diameter of 0.15mm was been used during TW-ECDM process and found that significant hike in cutting speed is obtained using coated wire. An ANOVA result also revealed that the highest contributing (65.79%) factor is voltage in influencing the material removal rate. And second most contributing factor is % of electrolyte concentration (31.48%). SEM images revealed that the high surface roughness is mainly due to presence of craters. Improper flushing may be reason for the craters.

Singh et al. [21] have used a vertical configuration of wire electrochemical discharge machining (W-ECDM) process with textured wire surface to machine the micro-slits on glass. The effects of process parameters like applied voltage, pulse on time, electrolyte concentration and feed rate were experimentally investigated on the size and geometry of micro-slits in terms of kerf overcut and straightness. Streak photography is used to analyze the discharging mechanism for textured and smooth wire surfaces. The simulation results revealed that the textured surface of wire electrode resulted in the breakdown of gas film from the textured surface of wire electrode generates spark discharges from the entire face of wire electrode due to intensification of localized electric fields. Second-order regression models were developed to determine the relationships between input process parameters and responses. The parametric combination of applied voltage of 48 V, pulse on time of 3 ms, feed rate of 3 mm/min. and electrolyte concentration of 15% wt./vol. was recommended to machine the micro-slits with minimum kerf overcut and maximum straightness using desirability approach.

N.S. Mitra et al. [22] have done analysis of travelling wire electrochemical discharge machining of hylam based composites using Taguchi method. In their experiments, pulse on time as percentage of total time, frequency, applied voltage, concentration of electrolyte and wire feed rate were taken as optimal input parameters. They observed that pulse on time and concentrations of electrolyte are significant factors for material removal rate whereas applied voltage, concentration of electrolyte and wire feed rate are significant factors for radial overcut. Contributions of control factors i.e pulse on time (14.99%), frequency(2.09%), applied voltage(41.56%), concentration of electrolyte(23.36%) and wire feed rate (10.39%)in multi quality characteristics (MQC) were observed. Optimal values observed for various control factors in overall improvement of MQC are pulse on time 70% of total pulse duration, 85Hz frequency, 50 V applied voltage, 30% by weight concentration of electrolyte and 50mm/sec wire feed rate.

Pallvita et al [23] machined the alumina epoxy nanocomposite (ANEC) using wire electrochemical spark machining. They used on one parameter at-a-time (OPAT) approach for conducting specific number of experiments to study the effect of voltage, electrolyte concentration, pulse on time and wire velocity on MRR and R_a using brass wire of 0.2mm diameter and NaOH electrolyte. They found that at higher voltage, material removal rate is high and more uneven surface obtained due to higher energy content produced at higher value of voltage. They also observed that MRR and surface roughness both increases with decrease in silica particle concentration. Also the MRR is less at lower pulses and higher wire velocity due to the less discharge energy availability at higher wire velocity.

IV. CONCLUSIONS AND FUTURE SCOPE

ECDM process can machine the hard to machine non-conducting material which is cost effective solution. The 3D machining with WECDM like WEDM is missing in the past research. Toxic fumes released during the experimentation leads to suffocation which demerits its commercial use, further handling and disposal of chemicals is also a problem. In most of the research repetitive parameters have been taken for the process evaluation, a very few literatures available on the gas film formation and its governing factors. Though various theories have been proposed to explain the mechanism of material removal, yet exact explanation about the process is not available. Further study can be done on vibration of wire tool in WECDM. Different wire materials, effect of surface texture of wire have not been explored yet.

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