Hybridization of Electro Chemical Machining and Electro Discharge Machining Processes - A Review

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Abstract

Advance manufacturing industries are facing challenges due to enriched mechanical, electrical and thermal properties of advanced engineering materials such as ceramics, super alloys, heat treated steels, composites etc. Even non-conventional machining processes have also been imposed by certain limitations while machining these advanced materials, such as electrical conductivity, hardness, brittleness etc. In present scenario manufacturing industries are demanding for quick and better results in order to produce good quality products with in the desirable tolerance limits and interchangeability. Electro-chemical spark machining (ECSM) process is a hybrid machining process perfectly capable of precisely machining complex shapes in hard and brittle materials irrespective of their electrical conductivity. ECSM process is a feasible combination of Electrical Discharge Machining (EDM) and Electro-chemical machining (ECM) process in which sparking action of EDM and electrolysis action of ECM occurs together. ECSM process has been successfully implemented for machining of non-conductive materials such as glass, quartz and ceramics as well as conductive materials such as steel 100Cr6. ECSM processes find wide applications for micro fabrication in the field of aeronautics, defence artilleries, surgical instruments, automobile industries, advanced machine tools, Nuclear power plants etc. In this paper, the capabilities, applications and qualitative limitations of various configurations of ECSM process such as Micro drilling ECSM, Micro milling ECSM and Wire slit ECSM have been discussed. Further, efforts have been made for clear understanding of basic physics of ECSM and future research possibilities in ECSM based Hybrid processes and related area for new scholars and researchers.

Keywords: EDM, ECM, ECSM, Hybrid machining processes (HMPs), Micromachining.

1. INTRODUCTION

Electrochemical Discharge machining process (ECDM) is a process suitable for machining as well as micromachining of electrically non-conductive materials. Besides the semiconductor technology, there are various processes for micromachining such as Reactive Ion Etching (RIE), chemical etching, plasma-enhanced chemical vapor deposition, spark assisted chemical engraving and micro-stereo lithography. Use of photoresist as sacrificial layer to realize micro-channels in micro fluidic systems is also available in literatures. All these methods are expensive as they need the vacuum, clean environment and mostly involve in between multi-processing steps to arrive at the final micro channel machining results.

The ECSM process is a standalone process unlike others that does not demand on intermediate processing steps such as masking, pattern transfer, passivation, sample preparation etc. The use of separate coolants is also not required in performing the micromachining by ECSM. Micromachining needs are forcing reconsideration of electrochemical techniques as a viable solution. Another similar process termed as spark assisted chemical engraving (SACE) (Wuthrich et al.,) [1] has been employed for the micromachining of glass. ECDM is a strong candidate for micro fabrication utilizing the best of electrochemical machining (ECM) and electro discharge machining (EDM) together. Applications of ECSM for micro fabrication can be in the field of aeronautics, mechanical, electrical engineering and similar others. It can successfully process hard and brittle materials including glass, silicon, molybdenum, quartz, alumina, advanced ceramics and many other materials.

The process can be explained in four steps.

i Electrolysis,
ii Generation and accumulation of hydrogen gas bubbles around the electrodes
iii Bubble coalesce and gas film formation
iv Discharge / Sparking.

A schematic diagram of the basic ECSM process is shown in the figure below.

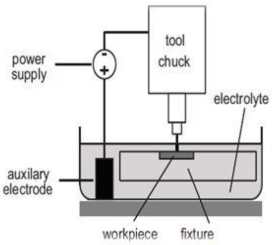

Fig.1: Schematic diagram of the basic ECSM process [3]

In ECSM process, the work piece is dipped in a base electrolyte like NaOH or KOH. A DC or pulsed voltage is applied between the tool-electrode and the counter electrode. The tool-electrode tip is dipped few millimeters in the electrolyte. The counter electrode is placed a few centimeters away from the tool-electrode.

2. MACHINING CAPABILITIES AND POSSIBILITIES

2.1. Micro Drilling

Yang, C.K. et al. [4] proposed using a tool electrode with a spherical end whose diameter is larger than that of its cylindrical body for micro drilling. Experimental results

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indicate that the curve surface of the spherical tool electrode reduces the contact area between the electrode and the workpiece, thus facilitating the flow of electrolyte to the electrode end and enables rapid formation of gas film. It overall significantly increases the efficiency of micro hole drilling. Comparison between machining depth of 500 mm achieved by conventional cylindrical tool electrode and the proposed spherical tool electrode shows that machining time was reduced by 83% while hole diameter was also decreased by 65%.

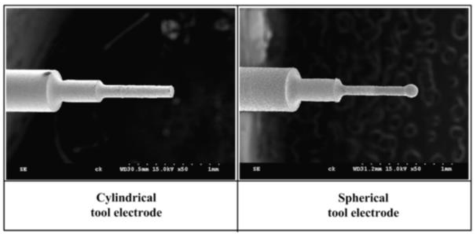

Fig. 6: SEM images of different tool electrode (a) Cylindrical (b) Spherical [4].

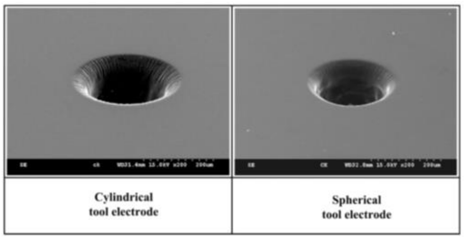

Fig. 7: SEM images of micro-holes machined by different tool electrodes [4].

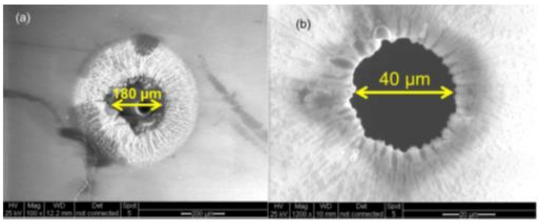

Fig. 8: High aspect ratio micro hole on 1.2 mm thick glass plate (a) entrance Ø 180 µm (b) exit Ø 40 µm [8].

Jui, Sumit K. et al. [8] have studied the high aspect ratio micro-hole drilling on glass. They achieved an aspect ratio of 11 while machining for deep micro-hole drilling on glass using low electrolyte concentration and micro tungsten tool. The results have shown that lower electrolyte concentration reduce overcut by 22%, thus increasing the aspect ratio of the micro holes. Lowering the electrolyte concentration also reduced the tool wear and hole taper by 39% and 18% respectively. Mohammad R. R. et al. [11] applied longitudinal oscillation to the cathode electrode during the electrochemical discharge micro drilling of glass and study the effects of electrolyte flushing alteration in both discharge and hydrodynamic regimes of the process. Two geometrically different tools including cylindrical rod and micro drill were used as machining electrode (cathode).

In the case of cylindrical rod, two types of longitudinal waveforms including square and sinusoidal ones were applied to the tool. The experiments were resulted in a noticeable improvement in material removal rate (MRR) using square waveform and a slight improvement in the case of sinusoidal wave form. Moreover, the obtained MRR by means of vibrating micro drill has been compared with those achieved by non-vibrating one in several oscillation frequencies and amplitudes.

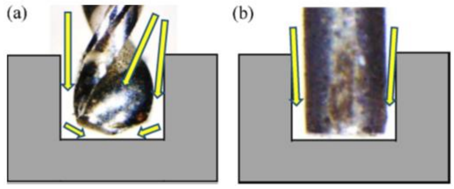

Fig. 9: Electrolyte flow in cylindrical rod and micro drill as cathode electrodes [11]

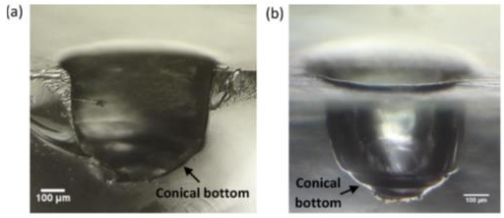

Fig. 10: (a) Cross section of a hole drilled by the micro drill, (b) side view of a hole drilled by the micro drill [11]

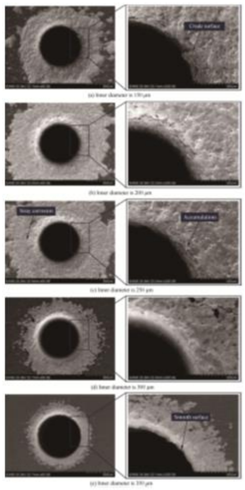

Fig. 11: SEM photographs of machined lateral surfaces using tube electrodes with different inner diameters [16].

The results showed that the vibration of the micro drill cannot further improve the electrolyte flushing and MRR in comparison with non-vibrating one because of the inherent electrolyte flushing in micro drill through its flutes which is constant in vibrating and non-vibrating cases. Zhang Y et al. [16] experimentally investigated the effects of inner diameter on the machining efficiency and surface quality of tube electrode high-speed electrochemical discharge drilling (TEHECDD). They developed a setup for micro drilling of nickel based super alloys aiming for the finding the possibility of using the process for machining of film cooling holes. Tube electrodes with the same outer diameter of 500 µm but with different inner diameters of 150, 200, 250, 300, 350 µm were fabricated and used in the TEHECDD. Based on the comparison experiments, the effects of the inner diameter on the machining efficiency and surface quality of TEHECDD were investigated. The results show that larger inner diameters could effectively improve the flushing condition and facilitate the removal of machining by-products. Therefore, higher material removal efficiency, surface quality, and electrode wear rate could be achieved by increasing the inner diameter of the tube electrode.

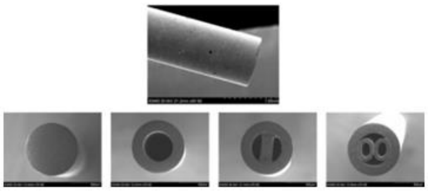

Fig. 12: Tool electrode with different inner shapes [17].

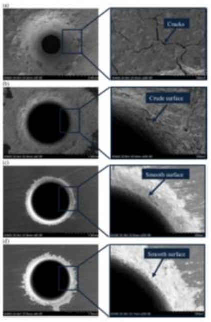

Fig. 13: SEM images of holes machined by four kinds of tool electrodes: (a) cylinder, (b) single-hole, (c) double-hole, and (d) multi-hole [17].

Zhang Y et al. [17] proposed improved tube electrodes for use in the TEHECDD process. All outer diameters are set to the same value (D = 1000 µm), whereas the inner diameters of the electrodes are designed as 200, 300, 400, 500, and 600 µm, and the interiors of the electrodes are designed to have different shapes, i.e. hole, single hole, double holes, and multi holes. The mechanism of the enhanced TEHECDD performance when using different tube-electrode inner shapes was analyzed, and the effects of different tube-electrode inner shapes on the machining performance were investigated. The results show that an increase in the tube electrode inner diameter results in a higher material removal rate, smaller average bore diameter, and smaller taper angle. However, for the single-hole tube electrode, a larger inner hole results in the formation of a residual cylinder. Thus, the double-hole and multi-hole tube electrodes are proposed and found to be effective in removing the residual cylinder.

2.2. Micro Milling

Abou Ziki et al. [6] demonstrated that the texture formed on the channel surface is a mimic of the electrolyte flow patterns induced during machining. The electrolyte viscosity is found to be the most significant factor influencing the channel texture among other factors i.e. inter electrode gap, machining voltage and tool travel speed. Pulsed voltage was also found to be influencing the surface texture. As a result, different channel surface textures were obtained during SACE machining by controlling the parameters. This work demonstrates the capability of SACE to both micro machine and texture glass surfaces in one machining operation. It was demonstrated that for low electrolyte concentration feathery like patterns were formed on the channel surface while for high electrolyte concentration spongy like porous texture is obtained. For high electrolyte concentrations cracks may form on the channel surface. It was concluded that the channels machined at low speed (5µmm/s) had a uniform surface texture and flat walls as compared to channels machined at higher speed (10µmm/s and 20 µmm/s).

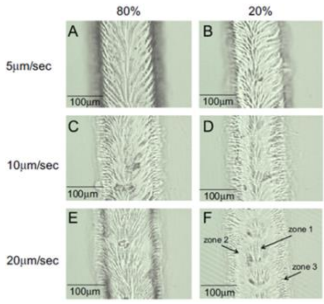

Fig. 14: Effect of tool travel speed on the surface texture for different pulse duty cycles (80% and 20%) at three tool speeds5 µmm/s, 10 µmm/s, and20 µmm/s while using 30V supply and 10 wt% NaOH [6]

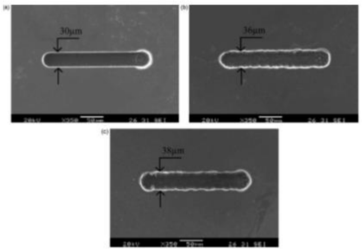

Fig. 15: Groove machined at (a) 23 V, (b) 25 V, and (c) 27V (KOH 30wt%, 1 ms/1ms pulse on/off-time ratio, Ø 22µm tool, 3µm/s feed rate, 25µm machined layer depth, and 300 rpm rotational speed [3].

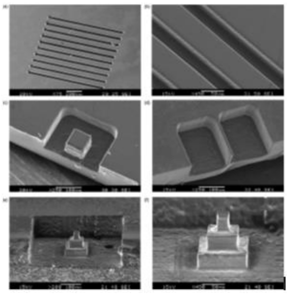

Fig. 16: (a) Micro-grooves, (b) enlarged figure of micro-grooves, (c) micro-pillar, (d) micro-wall, and (e and f) micro-pyramid machined on glass by ECDM (KOH 30 wt%, 23V pulse voltage, 1ms/1ms pulse on/off-time ratio, Ø 30–33µm tool, 3µm/s feed rate and 300rpm rotational speed) [3].

Cao XD et al [3] aimed the study of ECDM in order to improve the machining of 3D microstructures of glass. To minimize structures size and obtain good surface microstructures the effects of the electrolyte, pulse on/off-time ratio, voltage, feed rate, rotational speed, and electrolyte concentration in the drilling and milling processes were studied. To obtain a stable gas film over the whole surface of the tool at a low voltage a new mechanical contact detector, based on a load cell was used, the immersion depth of the tool electrode in the electrolyte was reduced as much as possible. Various micro-structures less than 100µm in size, such as Ø 60µm micro holes, a 10µm thin wall, and a 3D micro-structure were fabricated to demonstrate the potential for micro-machining of glass by ECDM. It was concluded that the use of pulse voltage reduces hole size and improves surface quality. Micro-holes with a 60µm diameter and a 150µm depth can be obtained with a 30V pulse voltage and a 1 ms/1ms pulse on/off-time ratio. In ECDM milling, 0.099µm R_a was obtained with a 23V pulse voltage. The KOH electrolyte gives a smaller machining gap than NaOH solution. The smallest machining gap, 15µm, was achieved in KOH30 wt%. In this study the machining feed rate was 3µm/s and the depth of the machining layer was 25µm.

2.3. Special Adaptations: Wire Slit ECDM

The use of wire electrochemical discharge machining (WECDM) to slice hard brittle materials has recently been studied because its effectiveness.

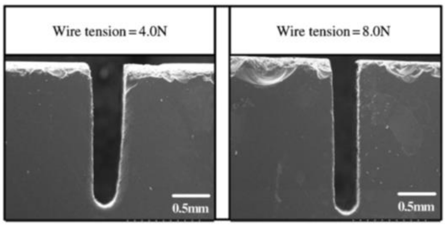

Fig. 17: SEM micrographs of slit given different wire tensions [2].

Materials with high hardness, brittleness, strength and electrical insulation, which are difficult to machine can be cut with ECDM. Many researchers worked on a WECDM to study its potential to slice hard brittle materials. One interesting theory was proposed by Yang C T et al. [2]. Their work aims to improve the over cut quality by adding SiC abrasive to the electrolyte. A mechanism that combines discharge, chemical etching and abrasive cutting was studied. The effects on expansion, roughness and material removal rate (MRR) are discussed. The experimental results reveal that adding abrasive reduces the slit expansion because it increases the critical voltage. The particles disrupt the bubble accumulation to form an isolating layer around the wire, increasing the critical voltage and reducing the discharge energy. The surface roughness is improved because the abrasive helps to refine the micro cracks and melted zone that is formed by discharge heat erosion. The quality of the slit can be controlled. The experiments conclude achieving 0.024mm expansion and 0.84µm Ra roughness of the slit.

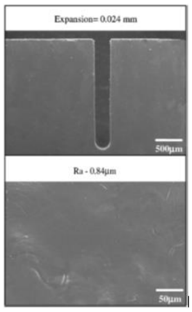

Fig. 18: SEM micrographs of slit in ECDM with abrasive [2].

3. PARAMETRIC CONCLUSIONS

Various machining and micromachining setup are available in literatures. Throughout research had been carried out to study different parameters affecting the ECDM process. Various machining parameters and their update researched conclusions are tabulated in Table 1.

Table 1: Machining parameters and their updated research conclusions

Tool electrode	✓ Tungsten carbide is most frequently used tool material in ECSM due to its high wear resistance, high temperature resistance, chemical inertness and significantly low specific heat capacity. ✓ Stainless steel, copper and brass materials are also often used as a tool material in ECSM process. ✓ Recently, coated tools like mild steel with abrasive coating, mild steel with nickel coating were used to improve the material removal rate in ECSM process by assisting in removing molten material from the machining zone in addition to removing softened material by scratching process.
Tool electrode shape	✓ Needle shaped tool-electrode is better at higher drilling speed for low voltages, the discharges are concentrated at the tip of the tool electrode. The discharge density is higher for smaller cross-sectional tool-electrodes that results in higher material removal rate. ✓ Promotion of electrolyte flow inside the micro hole was achieved by flat sidewall tool-electrode and helix micro tool-electrode ✓ Spherical headed tool-electrode reduces the contact between the tool-electrode and the work piece, and thus facilitates the flow of electrolyte to the tip of the tool-electrode.
Tool electrode motion	**Rotation** ✓ Tool-electrode rotation improves the machining performance of constant feed drilling. ✓ Tool rotation reduces the stray corrosion that results in almost accurate shape at hole's entrance and hole's exit. **Eccentric Rotation** ✓ Machined depth increases with an increase in eccentricity till the machined depth attained an optimum value at eccentricity distance approximately equal to the tool radius. ✓ As the eccentricity increases, the side space between tool and work piece gets widened that results in more quantity of fresh electrolyte flow into the machining zone which helps to flush out the debris produced. ✓
	✓ Increase in applied voltage increases the MRR due to generation of more hydrogen gas bubbles resulting

Voltage	in greater amount of discharge energy at the sparking zone. ✓ It was observed that when applied voltage is increased to 100 V, the MRR starts decreasing due to entrapping of debris in the spark gap. ✓ At high voltage, some micro-cracks will be produced in the machining zone due to excessive heat generation.
Electrolyte	✓ Preferred electrolytes are NaOH or KOH ✓ Electrolytes with higher pH values yield higher MRR. ✓ Acidic electrolytes, such as sulfuric acid and hydrochloric acid almost produce no machining while neutral electrolytes, such as KCl and NaCl produce a low MRR.
Electrolyte concentration	✓ The MRR increases with increase in electrolyte concentration as more electrochemical reactions occur between the cathode and the anode which generates greater number of sparks. This results in more gas bubbles at the sparking zone. ✓ As the concentration of electrolyte increases the electrolyte become more viscous that leads to smoother machined surface. ✓ Further increase in electrolyte concentration (25 % by weight) leads to decrease inactivity of EDM action resulting in lower MRR.
Tool feed	✓ If the feed rate is more than MRR of the drilling process, it leads to breaking either tool-electrode or the work piece. There are three different options adopted for tool feeding in ECSM. ✓ The first is the gravity-feed mechanism. In this, a constant feed force is applied to the tool-electrode, either through the self-weight of the tool or by attaching additional weight onto the tool, in order to ensure close contact between the tool-electrode and the work piece. ✓ In the second option, also called constant velocity feed, tool is fed using a separate tool feeding mechanism like stepper motor enabled drives which is independent of the instantaneous tool-work piece gap. No mechanical contact exists between the tool-electrode and the work piece. ✓ The third option is to control the tool feed as a function of the status of the actual machining process. The strategy, which may also be termed as adaptive feed strategy, is highly desirable for steady machining; however, it has been rarely used due to the complexity involved.
Effect of depth of hole	✓ In ECSM, the specified work material can be machined only up to a certain depth known as the “limiting depth” for a particular combination of applied voltage and electrolyte conductivity. ✓ The potential difference between the tool-electrode and the electrolyte decreases as the tool keeps penetrating inside the work material. This potential loss is mainly due to accumulation of gas bubbles on the tool-electrode that restricts the electrolyte flow to the tip of tool-electrode, which results in reduction of discharge activity and lowering chemical etching. ✓ Both effects result in lowering the MRR.
Effect of inter-electrode gap	✓ Increase in inter-electrode gap increases the inter-electrode resistance that affects the electrical conductivity of the electrolyte. ✓ As the inter-electrode resistance increases, the critical voltage required for gas film formation also increases that decreases the MRR. ✓ The 100 mm level was considered as the optimum level.

4. CONCLUSIONS

Use of ECSM process for machining of hard brittle and nonconductive is becoming a common practice. Difficult to machine materials like metal matrix composites and ceramics are also successfully machined with this process. From the above study of various configurations of ECSM process following conclusion can be drawn:

i Most frequently used electrolytes are NaOH and KOH as they are less hazardous.
ii Tungsten carbide tools are commonly used as tool electrodes due to their properties of high wear resistance and high temperature resistance.
iii Micro machining like drilling, milling and slicing are evidently explored in the literatures.
iv The ECSM technology is capable of generating sustainable spark precisely and in vicinity of conducting as well as non-conducting work materials which have endless machining possible utility.
v There are many machining possibilities of this process yet to be explored.

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