Advancement of Micro-ECDM Process: a Review Report

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Abstract: - Electro-chemical micro-machining (micro-ECDM) process appears to be very promising as a future micro-machining technique, since in many areas of applications it offers several advantages, which include better machining rate, precision and control and a wide range of non-conductive materials that can be machined. In this paper, a review is presented on current research, development and industrial practice in micro-ECDM. This paper focuses also the journey from ECDM to micro-ECDM research trends and the problematic areas of micro-ECDM. This paper shows some future possibilities of research on electrochemical discharge micro machining. This paper focuses mainly on different machining performance characteristics such as material removal rate, machining criteria, heat affected zone, surface roughness, gas film quality, machining depth, surface topography and tool wear. Micro-ECDM process can effectively be used for high precision machining operations. Some applications of micro-ECDM process have also been reported.

Keywords: *μ-ECDM, MRR, OC, SR, HAZ, TWR*

1. Introduction

Electrochemical Discharge micro-Machining (μ-ECDM) is a hybrid and non-traditional micro-machining process consisting of electro-chemical machining and electro-discharge machining. The material removal in μ-ECDM process occurs in the same way as that takes place in ECDM process. Material is removed due to the effects of electrical spark discharge (ESD) action and electrochemical (EC) reaction. From the analysis of the ECM, it has been found that there are two types of reactions usually occur in the system: electrochemical reactions at the electrodes and chemical reactions in the bulk of the electrolyte [1].

In µ-ECDM the electrolyte cell is similar to that used in ECM. When a voltage is applied to the cell with proper polarity, i.e. generally positive terminal as anode (auxiliary electrode) and negative terminal as cathode (tool), reduction of electrolyte with liberation of hydrogen gas takes place at the cathode tip. When the applied voltage is increased hydrogen gas bubbles grow in size. Their nucleation site density increases, current path gets restricted between cathode and electrolyte interface causing discharge to occur at this interface instantly. Thus, discharge in ECDM always occurs when the voltage in an electrolytic cell is increased beyond a threshold value [2, 3]. The basic mechanism of the process is not yet completely understood and is still a matter of research investigations. Various researchers have put forth explanations of ECDM phenomenon based on their experimental studies. Crichton and McGough [4] performed streak photography to get insight into the various stages of discharge by applying 85V pulse for duration of 200µs. They concluded that electrical discharge between cathode tool and electrolyte interface occurs due to: (i) generation of electrolytic gas at the surface of electrodes; (ii) the growth of layers of low ionic concentration near the electrodes and formation of oxide films on the anode surface; and (iii) the local variations in the electrolyte flow pattern caused by flow stagnation and eddy. Jain et al. [5] have considered each gas bubble as a valve, which after its breakdown due to high electric field produces discharge in the form of an arc. It is also mentioned that with breaking of each bubble, the discharge takes place. Tool is immersed just a fraction of millimetre below the liquid surface for a discharge to occur. But, the above mentioned observations, i.e. presence of large current spikes and the dependence of arc on immersion depth of tool, cannot be explained by the models proposed by Jain et al. [5] and Basak and Ghosh [6, 7].

Therefore, it is obvious that lot of aspects are still indistinct and lot of research works need to be conducted to reveal the basic mechanism of the ECDM process although the process is currently used as one of the micro-machining processes for machining of electrically non-conducting materials. Another experimental evidence for thermal mechanism in machining are the various observations of thermal cracks insides the machined materials [1,8-13] which are seen mainly at high voltage machining. This paper focuses on the fundamental mechanism of micro-ECDM process, influence of various process parameters on different machining characteristics and its some applications.

2. Effects of Different Process Parameters on MRR, OC, HAZ, TW, SR, Gas Film Quality, Machining Depth and Surface Topography in μ-ECDM

Figure-1 shows the ECDM set up. Present day research in μ-ECDM is focusing mainly on fabrication of variety of micro-products than basic research in μ-ECDM, which need to be addressed for higher process performance and better quality products. There are many factors, which affect the material removal rate (MRR), tool wear rate (TWR), accuracy (OC) and surface finish of final micro-machined features and gas film quality etc.

2.1 Material Removal Rate (MRR)

Applied voltage and electrolyte concentration have strong effect on MRR of micro-ECDM process. MRR increases with applied voltage while electrolyte concentration is fixed [17]. Initially the MRR is seen to be decreased with applied voltage at higher electrolyte concentration due to the possibility of material re-deposition at the machining zone. As shown in the Fig. 2 MRR increases with electrolyte concentration due to the fact that the conductivity of the electrolyte medium increases with electrolyte concentration and as a result, greater current flows through the path between the tool and the auxiliary electrode. An increase in the inter-electrode gap (IEG) lowers the flow of electric current hence MRR decreases [17-19]. Here, the resistance in the current flow path increases as a result of increase in IEG.

Material removal rate varies with the pulse frequency because the duration of the discharge increases as the frequency decreases, even though the total time that voltage is applied remains the same [20]. Also, MRR is increased significantly with the help of the vibration of gravity feed tool [21] and due to increase in drilling speed [22]. But, it decreases as the duty ratio decreases [20]. Yang et al. [23] investigated on Glass (Borosilicate) MRR=1.5 mg/min. In Glass (soda-lime, Alumina) MRR increases up to 30% Elec. Con. for micro drilling [24]. For trepanning of alumina and quartz the machining rate (MR) is 122.7 mg in 70 min [25]. The governing factor for MR in ceramics is Porosity [26]. Abrasive coated tools improved performance of MRR [27]. MRR of 0.06mm^3/min for alumina ceramic with Ra = 3.5 μm [28]. MRR increases with rise in inductance and lowers with rise in tool diameter [29].

2.2 Heat Affected Zone (HAZ)

Large amount of heat is generated while machining the ceramic materials by micro-ECDM. The heat-affected zone (HAZ) is formed around the machined zone due to the heat energy conducted to the workpiece during sparking and micro-cracks are produced within this zone. HAZ increases with an increase in applied voltage due to a higher intensity of sparking [17, 18]. HAZ also varies with electrolyte concentration as shown in Fig 3. HAZ decreases initially with increase in concentration, gets maximized and then starts to increase with increase in concentration.

HAZ increases as the duty ratio increases and the voltage pulse frequency decreases although the amount of time required for drilling a hole will increase because the removal rate decreases [20]. The micro-drilled surface gets rougher as the thermal damage in the HAZ increases. The tool material has an influence on HAZ. HAZ (Fig. 4) is reduced for Tungsten Carbide tool than Tungsten and Stainless Steel tool. Fig.5 shows a replica of a complex-shaped channel. Here, the impressions around the channel are visible. Besides the dark micro-channel, the adjacent surface modification seen [30].

2.3 Overcut (OC)

Overcut (OC) during micro-ECDM operations increases with an increase in applied voltage because of the fact that at high voltage a large number of gas bubbles are generated at the tool's sidewall. This may increase the possibility of stray sparking and thus causes more OC. Overcut is observed small under high voltage and low IEG compared to that under high applied voltage and high IEG [17-18]. Resistance-capacitor circuit is found to be suitable in micro-ECDM process for low overcut [19]. Different tool geometry and workpiece material are another reason for the overcut. Fig. 8 represents the effect of different tool-materials and voltage on OC. Spherical tool and cylindrical tools have different size of overcut on the workpiece as shown in Fig. 6. Fig. 7 displays the SEM images of the contours machined under different magnetic field configurations

The combination of pulse voltage and side insulation demonstrated a significant effect on the reduction of overcut in the ECDM drilling process shown in Fig.9. By utilizing a side-insulated electrode the tapering, overcut and roundness error of the holes were significantly reduced[34]. Radial overcut is increased with the increase the voltage and electrolyte conductivity [35]

2.4 Tool Wear (TW)

Tool wear of tool electrode can be assessed by changes at electrode end and in tool diameter, both of which affect gas film structure and machining stability, especially for gravity-feed micro-hole drilling [21]. The corner of electrode end has the highest current density and suffers the greatest wear. Fig. 10 exhibits the variation of tool wear on different tool electrode such as tungsten, stainless steel, tungsten carbide. Among the three materials, stainless steel not only has the lowest melting point and thermal conductivity, but also the least hard. Hence, it has the greatest wear, resulting also in its worst machining stability. Tungsten carbide does not have the largest thermal conductivity, its melting point is high, only second to tungsten, which exceeds 3000^{0}C and it achieves the best strength and hardness, thus contributing to its resistance against tool wear under high-temperature gravity-feed machining [31].

2.5 Surface Roughness (SR)

In μ-ECDM process, the locally concentrated spark energy causes irregularity of machined surface due to the micro-cracks, local fracture and breakage of the workpiece. Micro-cracks and fractures on the machined surface of the workpiece can be decreased by use of the conductive particles. A power-mixed electro-chemical discharge machining method to fabricate glass micro surface has been proposed by Han et al [36] and Yang et al. [37]. As a result the presence of conductive particles within the hydrogen film reduces the critical breakdown strength resulting in the decreased spark energy per single discharge pulse. The hydrogen film at the moment of discharge is modelled as breakdown of the insulating gas between two parallel plates for which distance of the gap becomes the theoretical thickness of the film. The presence of conductive particles reduces the dielectric strength of the film. By use of 1.0 wt.% graphite powder concentration in 30% NaOH, the number of micro-cracks is significantly reduced and the surface roughness is improved from 4.86 to 1.44 μm [36] as shown in Fig. 11. Fig. 12 shows a cut section of a replica of another machined surface. Here, the fragmented nature of the surface is clearly seen.

2.6 Gas Film Quality

Quality of gas film is the dominant factor that determines the machining qualities such as geometric accuracy, surface roughness and repeatability. A stable and dense gas film can be obtained when the applied voltage exceeds the critical voltage and reaches a specific level, which is called the ‘‘transition voltage’’. The thinner gas film thickness will result in lower fluctuations of discharge activities [38]. If the gas film thickness reduces then more reproducible machining is obtained. At lower applied voltage of 30–35V, the generation of electrolysis bubbles is less intense. As applied voltage reaches 40V, the generation of electrolysis bubbles becomes more intense. With further increase in applied Voltage (<40 V), drastic light emission is observed around the tool, as shown in Fig. 16. A greater quantity of (OH)- ions will reduce the surface tension of electrolyte, thus achieving a thinner gas film and an improved machining accuracy and increase in amount of (OH)- ions will enhance efficiency of chemical etching, thus producing a smoother machined surface. This phenomenon totally depends on the availability of electrolyte in the machining zone. Better electrolyte circulation in the micro-hole achieved by utilizing the flat-side wall tool can ameliorate deterioration of gas film quality, while ensuring stable discharge activity, which in turn enhances repeatability of micro-ECDM [39]. Figure 15 shows the image of gas film formation using a conventional tungsten carbide (WC) electrode, 0.2 mm in diameter, arranged according to the tool immersion depth [40]. The gas film geometries with and without ultrasound were visually compared for the tool immersion depth (e.g., l = 3 mm) using an optical microscope, as depicted in figure 14[40].

A side-insulated electrode efficiently prevents stray electrolysis and stabilizes the geometry of the gas film by attaining a regular bubble coalescence rate, as well as a uniform active tool surface and the sidewall of the tool is electrically insulated using a ceramic tube, shown in Fig.13 [40]

Wüthrich et al. [41] documented that adding surfactant to the electrolyte in the spark-assisted chemical engraving process could reduce the gas film thickness. By adding a constant voltage (offset voltage) at T_{off} duration, the gas film stability can be substantially promoted [42]. The gas film is more stable at high terminal voltages whereas its formation time decreases with it [43]. The mean building time of the gas film itself indicates that it diminishes asymptotically with the applied voltage.

2.7 Machining depth

Micro-holes in glass with a depth of 450 μm are drilled in less than 20 s. At the same time, better electrolyte circulation can prevent deterioration of gas film quality with increasing machining depth, while ensuring stable electrochemical discharge [33]. Figures 18 and 17 show the relationship between the machining time and the entrance diameter, respectively, with machining depth under different magnetic field configurations. In case 1, when machining depth is below400 μm, the bubbles inside the hole can easily escape, and there is no problem with circulation of electrolyte.

2.8 Surface Topography

The typical FESEM micrograph of the channel and debris are shown in Fig. 19 and Fig. 20 respectively. The micro cracks and craters are seen in the micrograph of the channel (Fig. 19), which is due to the thermal mode of material removal during the sparking process. Some bright edges are visible which are primarily due to the etching effect of the chemical, which are more prominently observed towards the edges at the grain boundaries where etching is predominant.

After the experimentation, the electrolyte used was collected and allowed to settle. The micro-debris was carefully filtered out and dried. The EDS was carried out on these powdered debris and micro channels obtained were also subjected to EDS. The FESEM results give useful inputs on failure modes. Small composition of Fe was seen as a result of tool-wear [44]. More craters are found on the side close to the work piece. The two SEM photos in Fig. 21 show the cut-in slot and the microstructure on the side surface with the KOH electrolyte. The surface microstructures of the specimen before and after the TW-ECDM process are shown in Fig. 22. It is vivid that the surface is coarser after machining and the surface roughness (Ra) is about 3.5micro-m.

3. Applications of μ-ECDM

The hybrid technology of micro-ECDM process consisting of EC reaction and ESD helps in micro-drilling on electrically non-conductive advanced ceramics like Alumina (Al_2O_3), Zirconia (ZrO_2), Silicon Nitride (Si_3N_4) and Silicon Carbide (SiC) etc [17, 18, 46]. Its unique feature of using thermal energy to machine electrically non-conductive parts regardless of their hardness has been its distinctive advantage in the manufacture of mould, die, automotive, aerospace, and surgical components. Fig.23 represents Various micro operation can be performaned by ECDM.

The micro-ECDM can be effectively used for high precision machining operations such as making grooves, micro-channels and 3D micro-machining, and also in various applications [47, 48]. Fig. 24 and 25 exhibit some example of micro-features generated by micro-ECDM process on glass. Micro channel formation and surface treatment can be done by micro-ECDM [49]. Glass-based micro-fluidic systems can produce by ECDM [50]

Also, this process can be applied for nano-deposition [51] and dressing of metal bond micro-grinding tool [52] and fabrication of micro-fluidic components [53]. Fig.26 shows the 450 μm diameter micro hole achieved on a piece of tantalum 1 mm thick. It was fabricated with a Pt tool, at 55 V, with a 17% NaOH concentration [54]. A comparative review of electrochemical processes (electrochemical, electro discharge, electrochemical spark) is presented in [55] for its application in micromachining. Fig. 27 shows the "8-shaped" micro channel formed on the soda lime glass at 55 V,17% electrolyte concentration, and 25 μm/sec table speed. It shows inner and outer diameters D_i = 1558 μm and D_o =2453 μm, respectively, width at junction W_j = 455 μm and that of micro channel = 405 μm [54, 56]. They are 3000 μm in length and vary in width from 635 to 682 μm [54]. A novel technology for micro machining of glass, called spark assisted chemical engraving (SACE) using ECS [57] is presented. Fig. 28 (A) shows the Pattern machined at 30V [57] and (B) shows Channels for micro reactor application [57]. In Fig. 29, a notch is visible in the machining area. This notch is also difficult to visualize with optical techniques [30].The hole was fabricated with a Pt tool, at 55 V 17% NaOH concentration. The entry and exit hole was 450 μm in diameter [54]. The shape of micro hole was improved by using the micro tool electrode diameter and length are 20 μm and 1.6 mm [58].For milling 3D metallic micro-structures machining efficiency is improved greatly due to the high processing energy and high tool feed rate by combined of micro-EDM and micro-ECM [59]. Fig. 30 Microscope images of the most micro hole by ECDM with machining-stop system[58].

The micro-ECDM process has potential usage in number of areas, such as: Micro fabrication of miniature machine tools for micro machining, micro fabrication of array of holes in SU-8 material to fabricate micro filters needed in micro-EDM process, micro seam welding of copper plates & foils, fabrication of miniature components and heat treatment. Jana *et al.* [61] have shown that electrolyte viscosity was the most significant factor influencing the channel texture and the significance of channel micro-texturing in micro-fluidics and biomedical applications

4. Conclusions

Results of recent research indicate that the applications of material removal in micro-machining of electrically non-conductive advanced ceramics and glass offer many opportunities that have been unexplored till now. Extensive research efforts and continuing advancements in the area of micro-ECDM for effective utilization in micro-fabrication require monitoring and control of the gas film, control of material removal and accuracy, improvement in HAZ and surface roughness are expected to enhance the application of micro-ECDM technology in modern industries. The increasing demands for precision manufacturing of micro-parts for biomedical and automotive components will lead modern manufacturing engineers to utilizing micro-ECDM technique more successfully considering its advantages, i.e. quality, productivity and ultimately cost efficiency, which are still vital for success in a competitive environment. In the last fifteen years most of the research articles of micro-ECDMing were represented with the discussion of the effect of various process parameters which effect on the machining criteria of MRR,OC,HAZ,TWR,MD,GFQ,ST and material removal mechanism (MRM). But it is not fully clear to the researcher about this micro-machining phenomenon. They investigated again and again. Reviewing their research paper we can concluded that some researcher done the analysis about this machining phenomenon given the various name such as micro-ECSM, SACE, ECSD, TWECDM, ECAM and EDM + ECM etc. By their experimental investigation they did only 25% work on MRR, 21% on OC, 15% on HAZ, 6% on TWR, 18% on GFQ, 6% on ST, 3% on MD and 6% on SR which is shown in Fig.31. Most of the researcher experiment on glass (66%), ceramics (13%), nano particles (3%), quartz (9%), alloy (6%) and composites (3%) refer to Fig.32. But now a day's various non-conductive materials are used in modern industrial field on which investigation is needed.

5. Future Research Scope in Micro-ECDM

In the modern industrial field there is a trend to use advanced engineering materials for product design. The knowledge of processing behavior of the advanced material often lags behind their usages in industry. Based on the review of current literature and assessment of the challenges, it is felt that the following research areas will be coping in the future research:

(1) To improve the machining depth.

(2) To machine non-conductive material by Multipoint cutting tool by micro-ECDM process.

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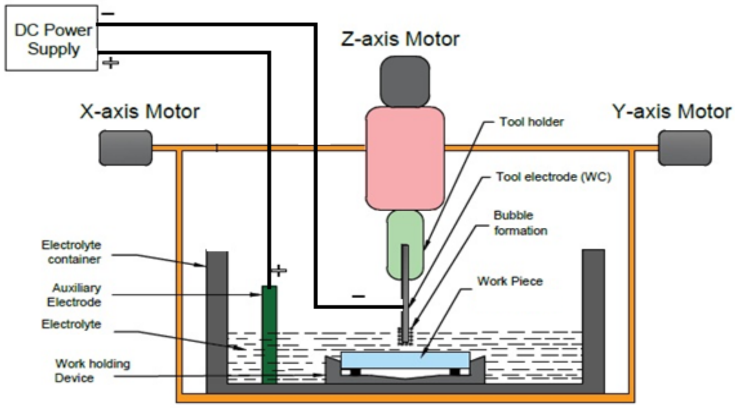


Fig.1 ECDM set up Schematic Diagram

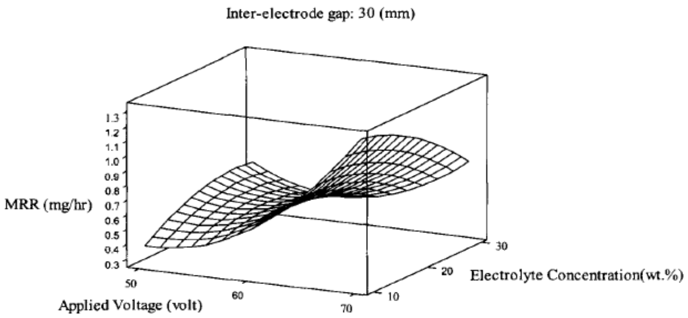


Fig. 2 Effect of applied voltage and electrolyte concentration on MRR [17]

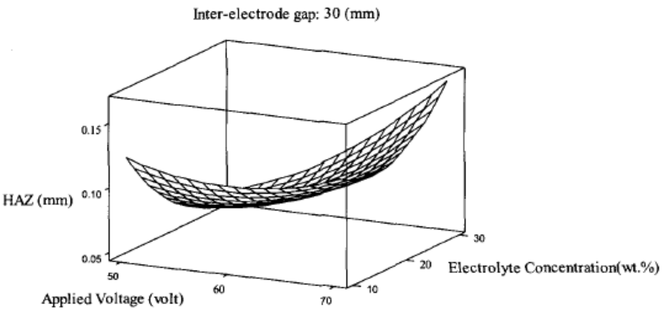


Fig. 3 Effect of applied voltage and electrolyte concentration on HAZ [17]

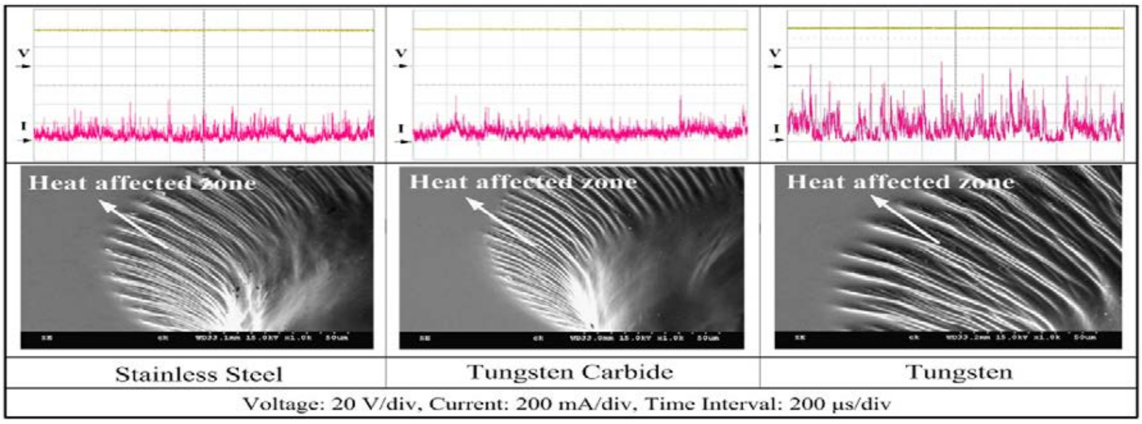


Fig. 4 Current responses at optimal voltage and SEM images of HAZ [31]

Fig.5. Replica of a complex shaped micro channel surrounded by HAZ [30]

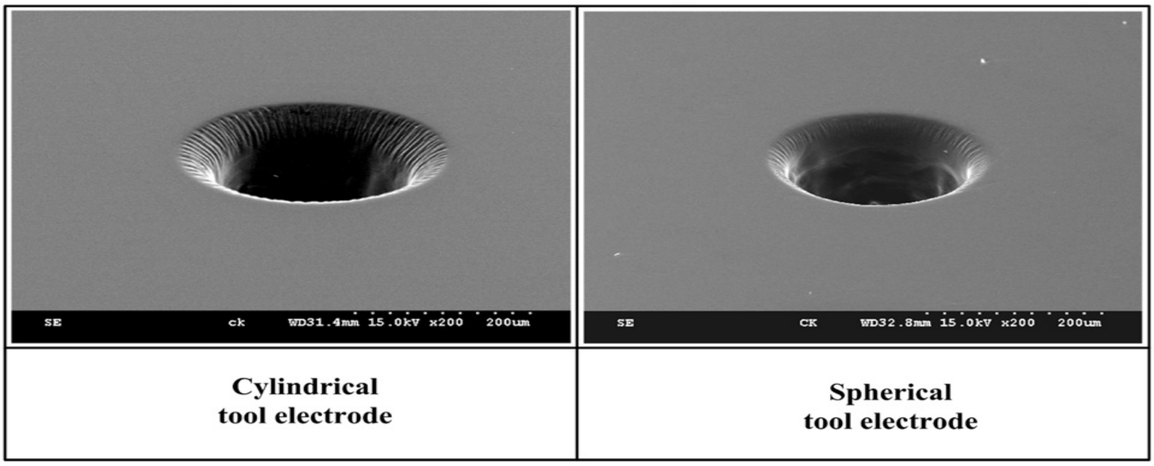


Fig. 6 SEM images of micro-holes machined by different tool electrodes [32]

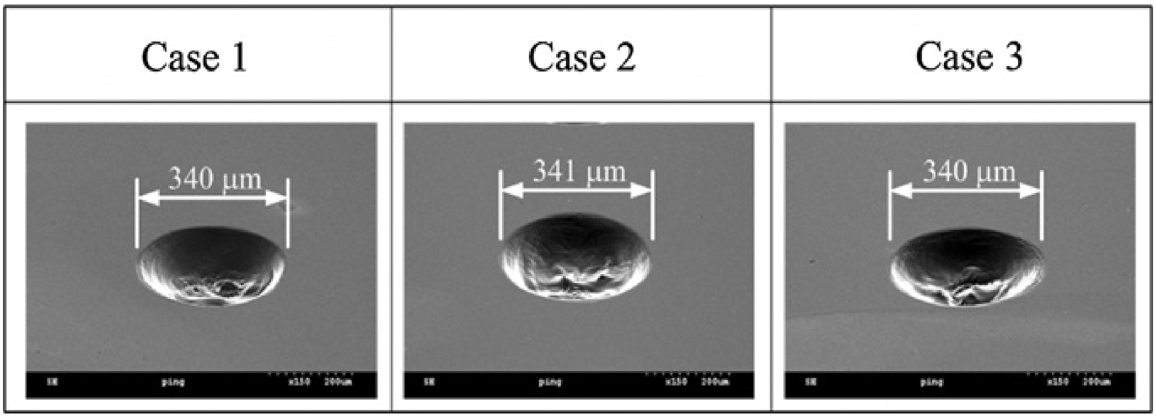


Fig.7. SEM images of the micro-hole machined under different magnetic configurations [33].

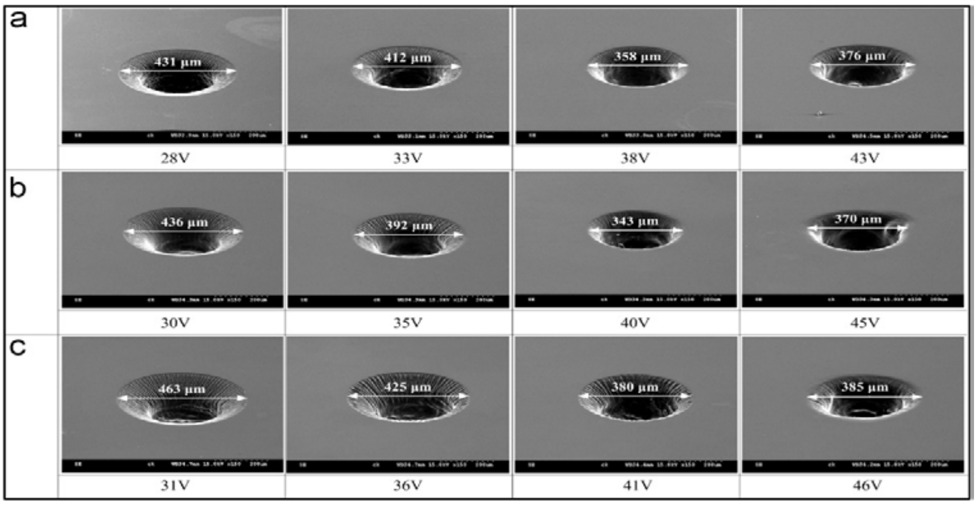


Fig. 8 SEM images of micro-hole at different machining voltages: (a) stainless steel, (b) tungsten carbide and (c) tungsten [31]

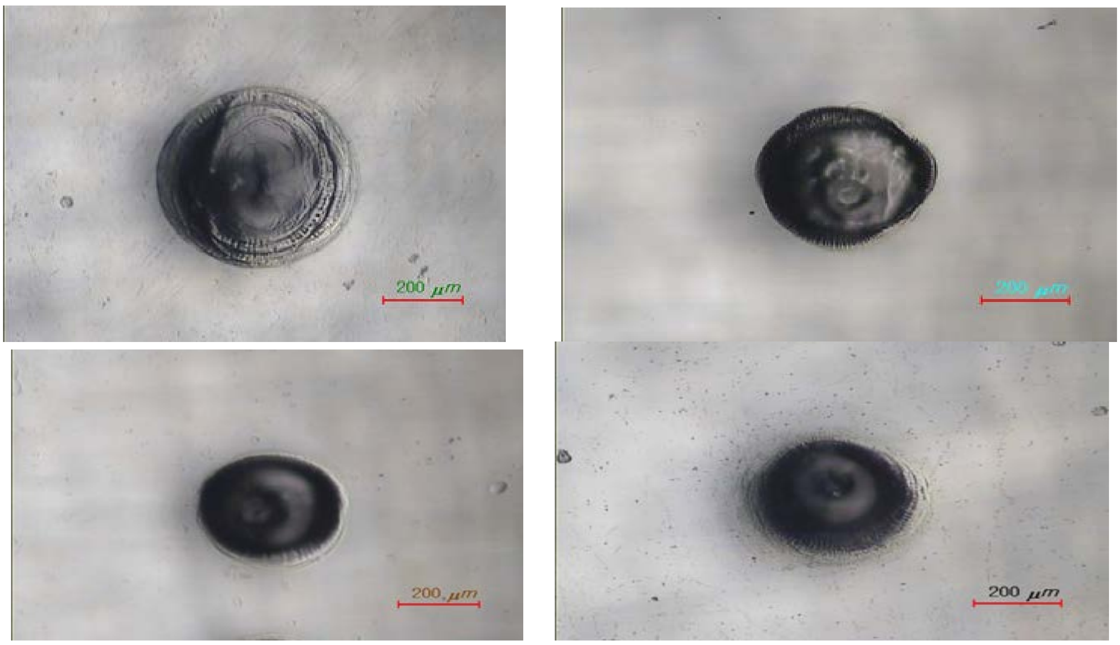


Fig. 9. Top view of the machined hole at 35V DC (*a*) Conventional electrode (left: continuous voltage, right: pulse Voltage). (*b*) Side insulated electrode (left: continuous voltage, Right: pulse voltage) [34].

Fig. 10 Variations in tool wear for different tool electrodes: (a) stainless steel, (b) tungsten carbide and (c) tungsten [31]

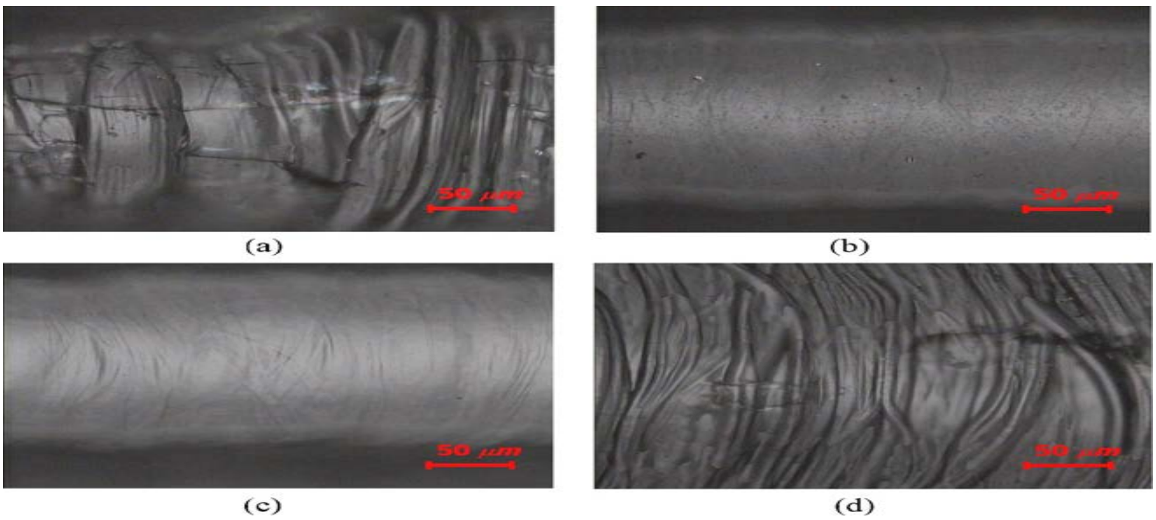


Fig. 11 Comparison of SR w.r.t. powder concentration: (a) without powder, R_a: 4.86µm; (b) powder: 5wt%, R_a: 1.63µm; (c) powder: 1wt%, R_a: 1.44µm and (d) powder: 2wt%, R_a: 5.26µm [36]

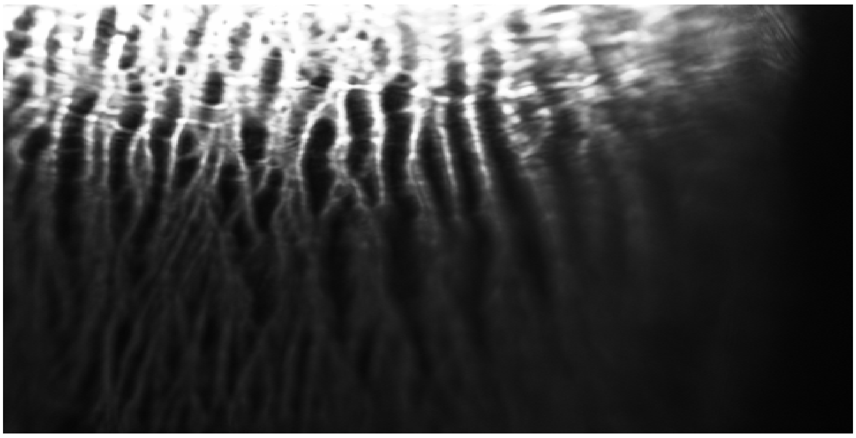


Fig.12. Fractal nature of micro channels replica showing the branching as surface modification [30].

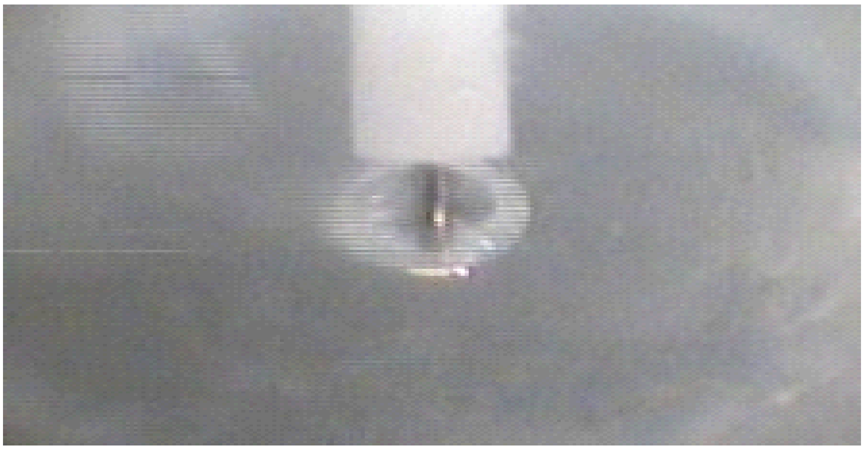


Fig.13. Geometric model of a gas film using a side-insulated electrode. [40]

(a) (b)

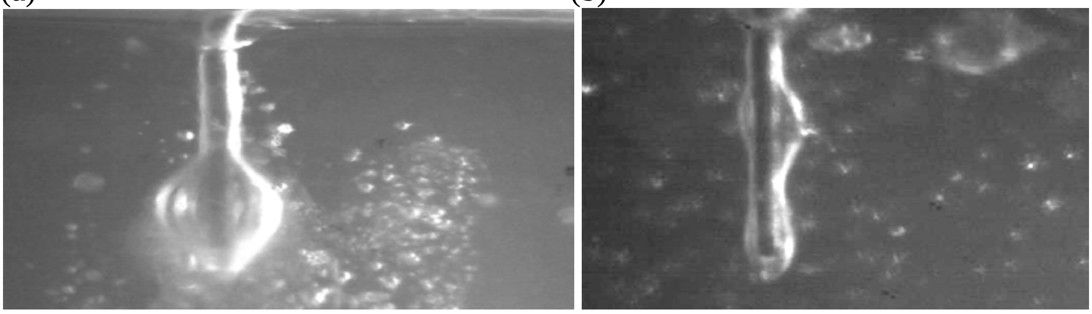


Fig. 14. Comparison of gas film formation phenomena with and without ultrasonic vibration effects. (*a*) Without ultrasonic. (*b*) With ultrasonic.[40]

(a) (b) (c)

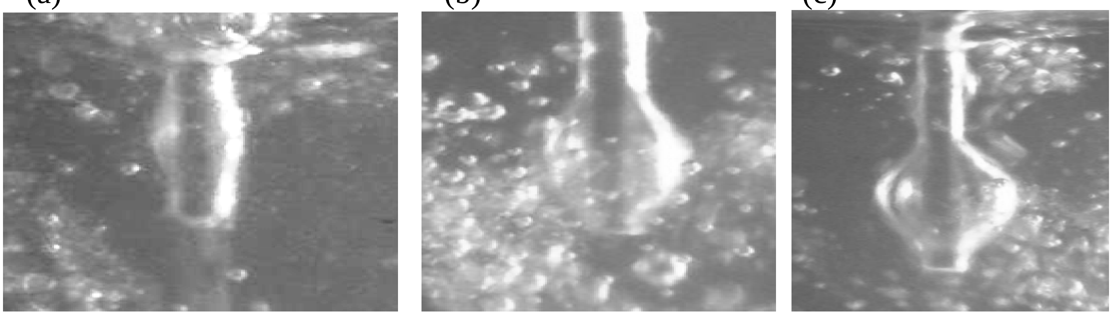


Fig.15. Images of gas film formation using a conventional electrode. (*a*) the current peak value is 1 A. (*b*) the current peak value is 3 A. (*c*) the current peak value is 6 A. [40]

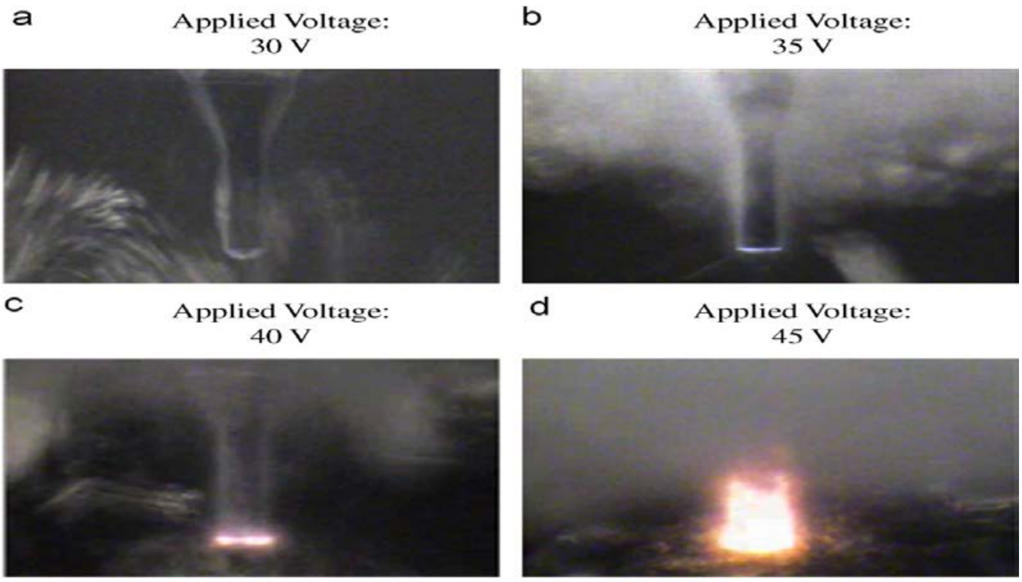


Fig. 16 Gas film morphology obtained at different voltages (cylindrical tool: Φ=200 mm, electrolyte: 5M KOH, tool immersion depth: 2mm) [39]

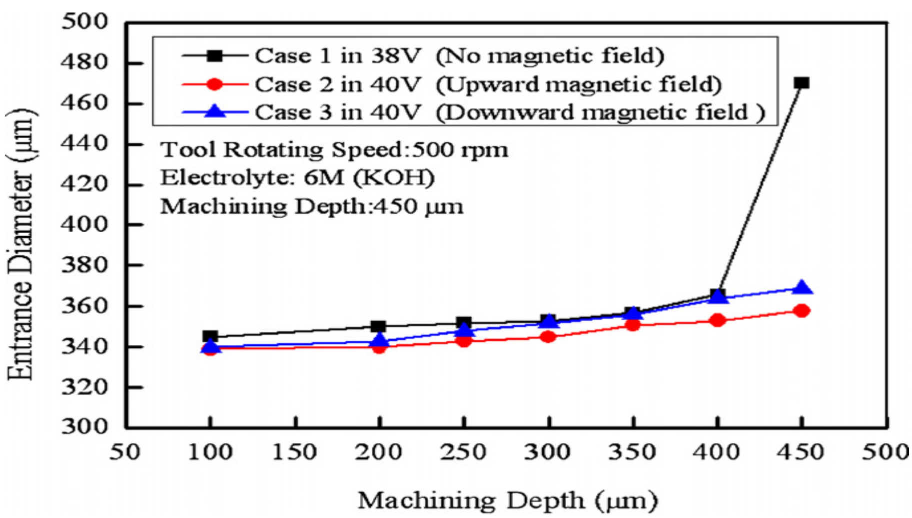


Fig.17. Relationship between the entrance diameter and the machining depth under different magnetic field configurations [33]

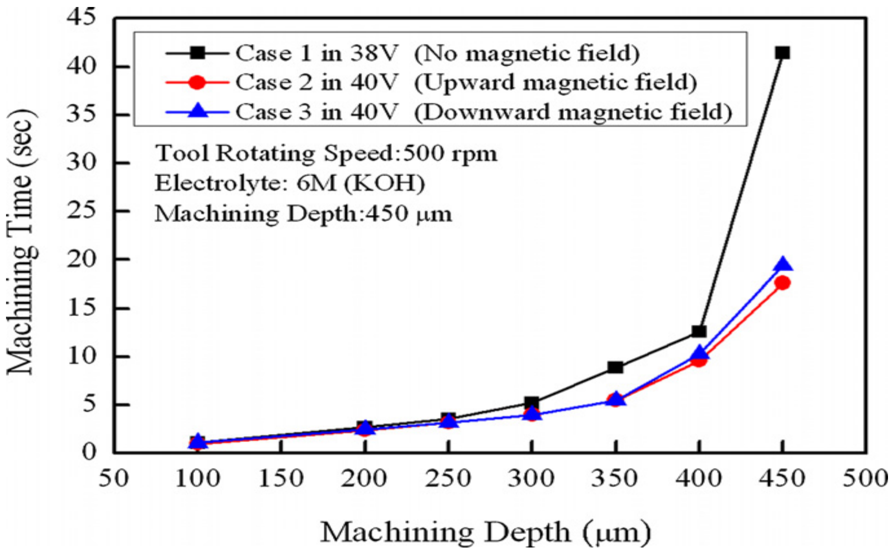


Fig.18. Relationship between the machining time and the Machining depth under different magnetic field configurations [33]

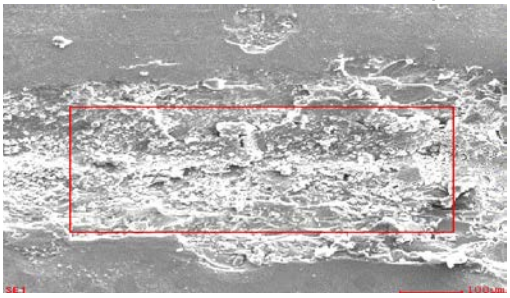


Fig. 19 FESEM micrograph of channel [44]

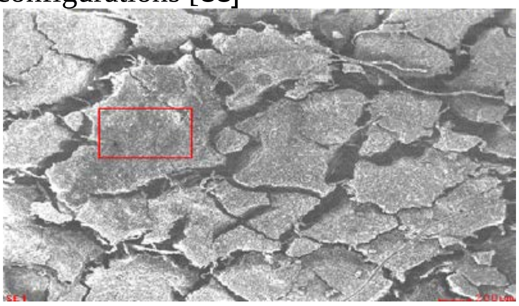


Fig. 20 FESEM micrograph of debris [44

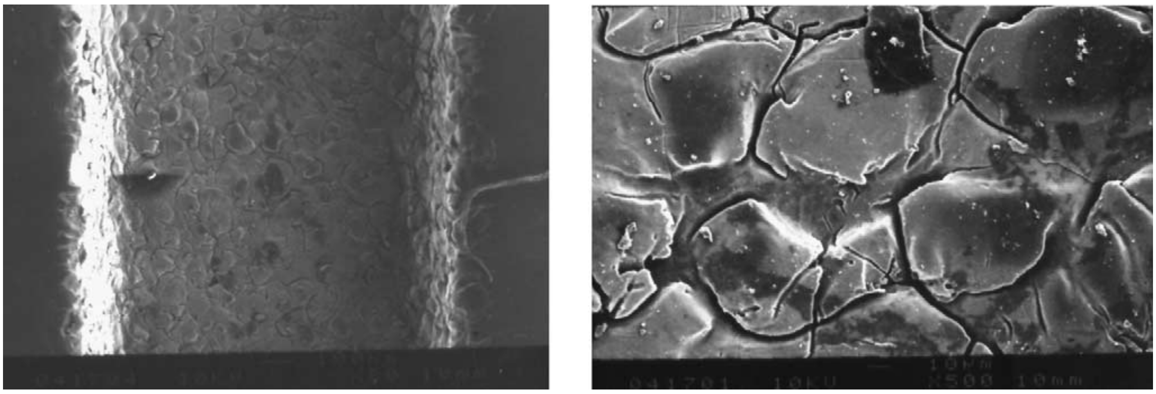


Fig.21. The cutting slot and microstructure of the borosilicate glass.[45]

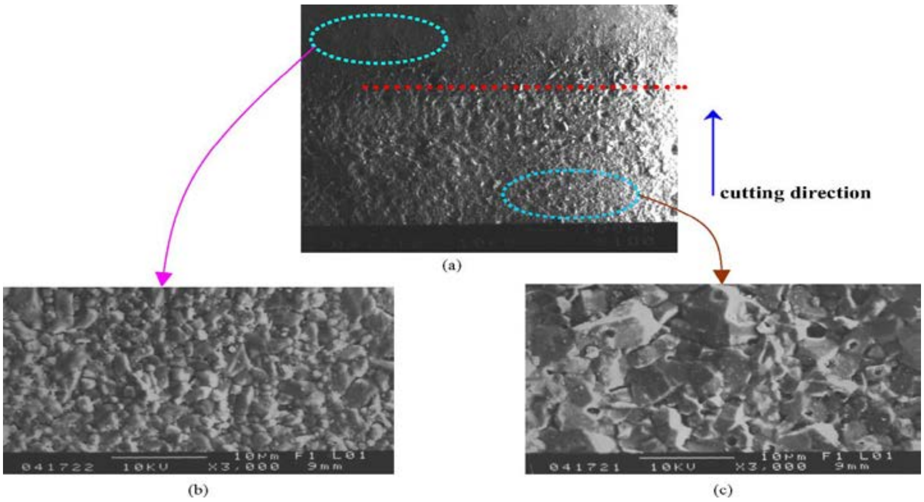


Fig.22. The microstructure of the Al_2O_3 ceramics before and after TW-ECDM testing [45]

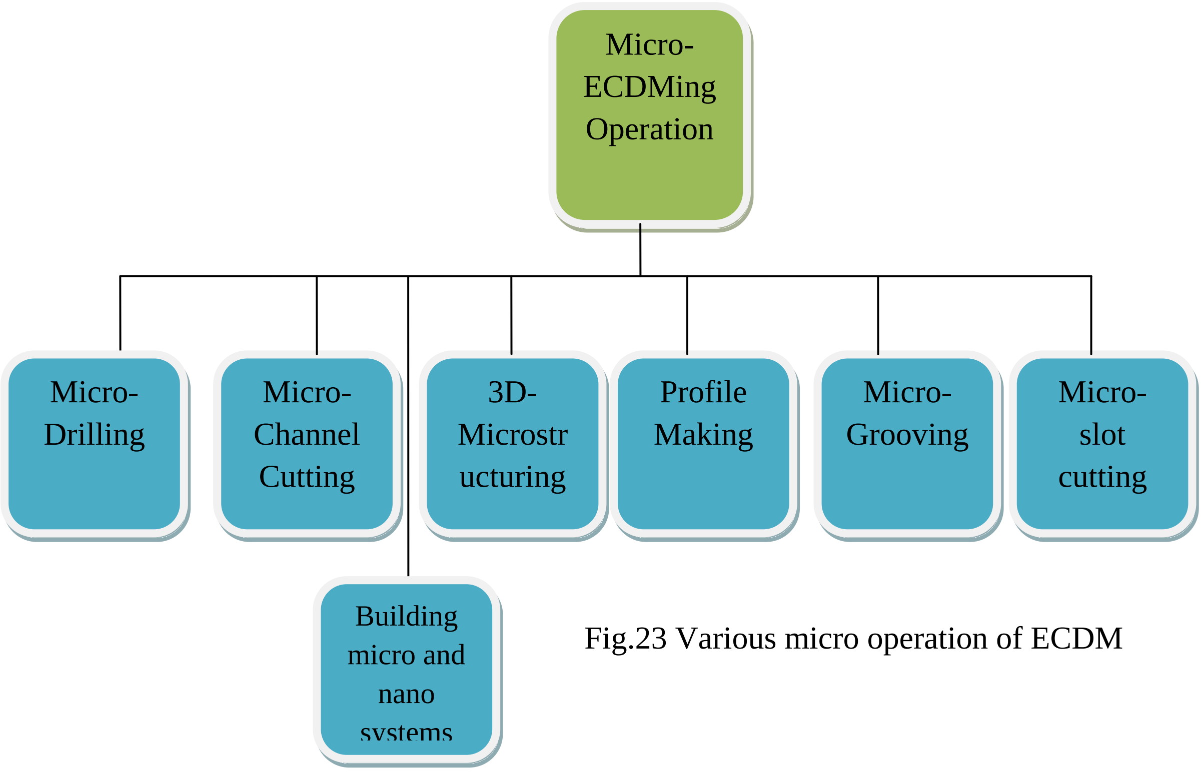


Fig.23 Various micro operation of ECDM

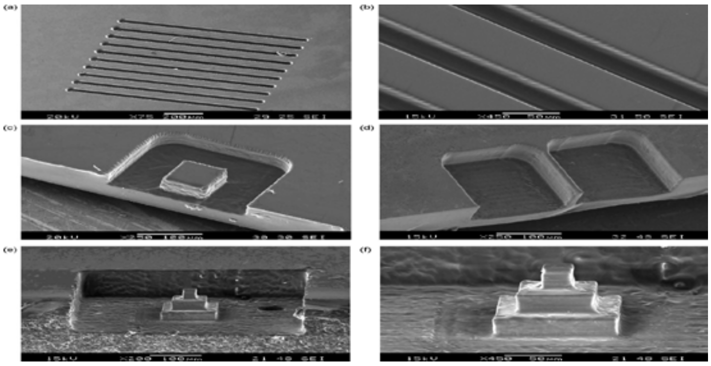


Fig. 24 (a & b) Micro-grooves, (c) micro-pillar, (d) micro-wall and (e & f) micro-pyramid machined on glass by μ-ECDM [47]

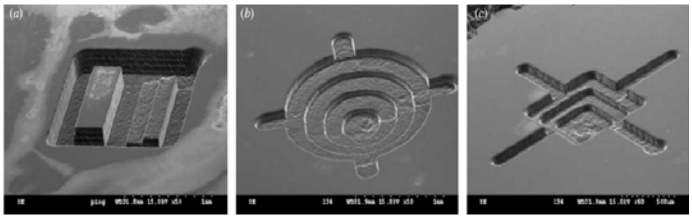
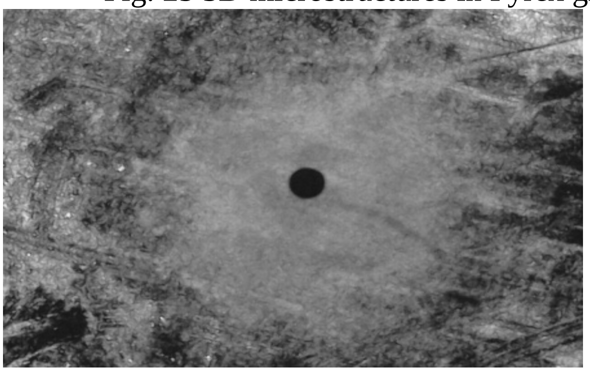


Fig. 25 3D microstructures in Pyrex glass machined using μ-ECDM [48]



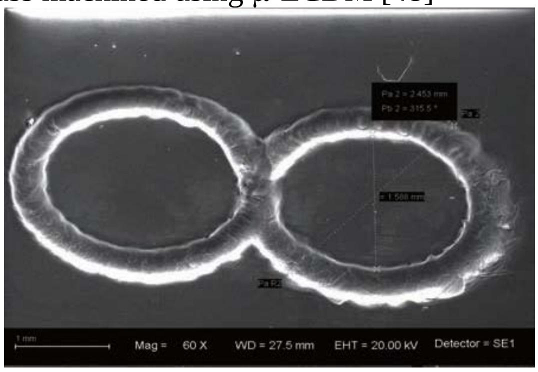
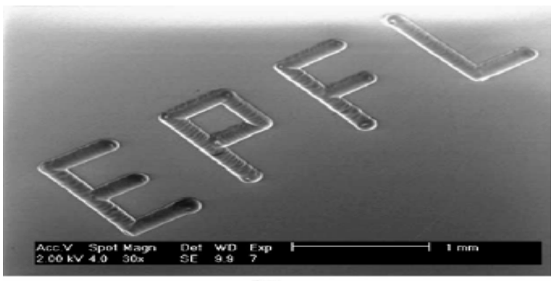
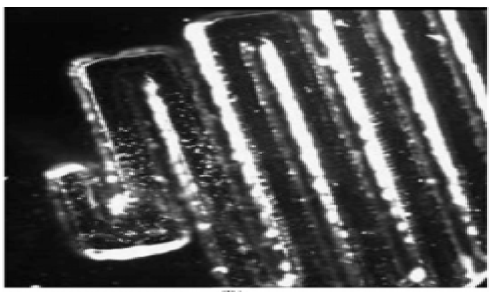


Fig.26. Microhole on a 1 mm thickness of tantalum [60]. **Fig.27**. SEM “8-shaped” micro channel [54,56,60]



(A)



(B)

Fig. 28 (A) Pattern machined at 30V [57] (B) Channels for micro reactor application [57]

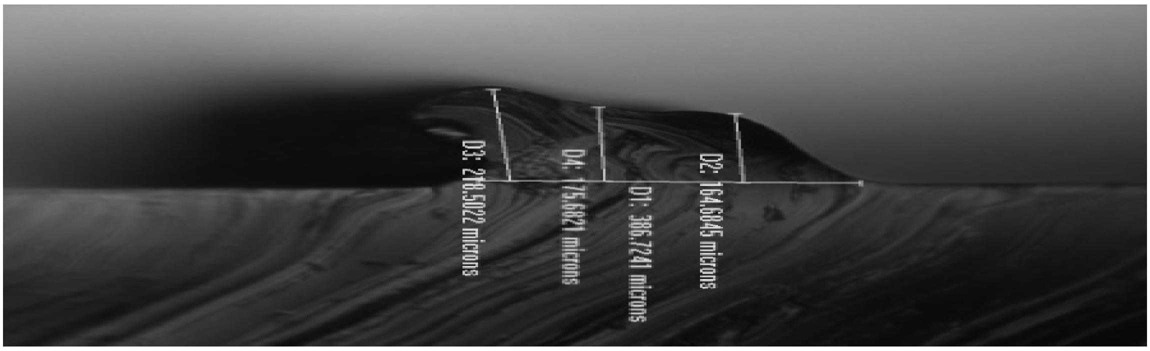
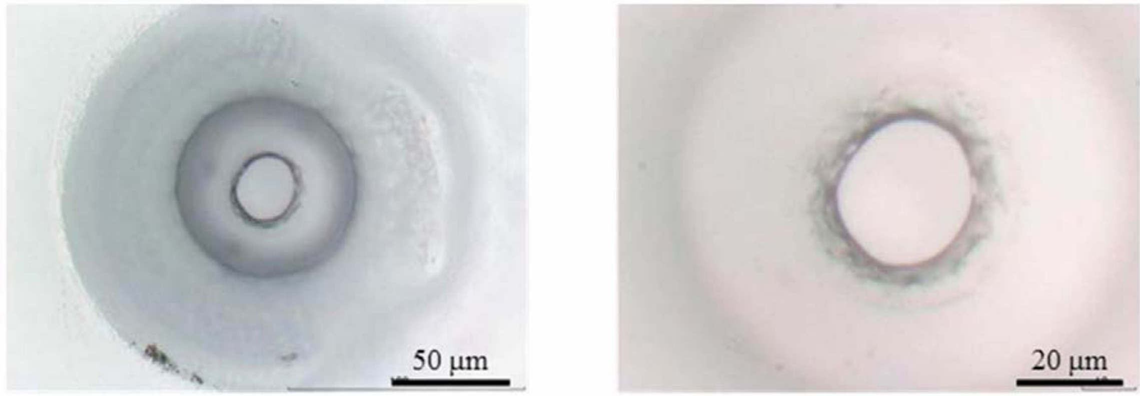


Fig.29A notch type of channel [30].



(a) Entrance side (b) Exit side

Fig. 30 Microscope images of the micro hole by ECDM with machining-stop system[58].

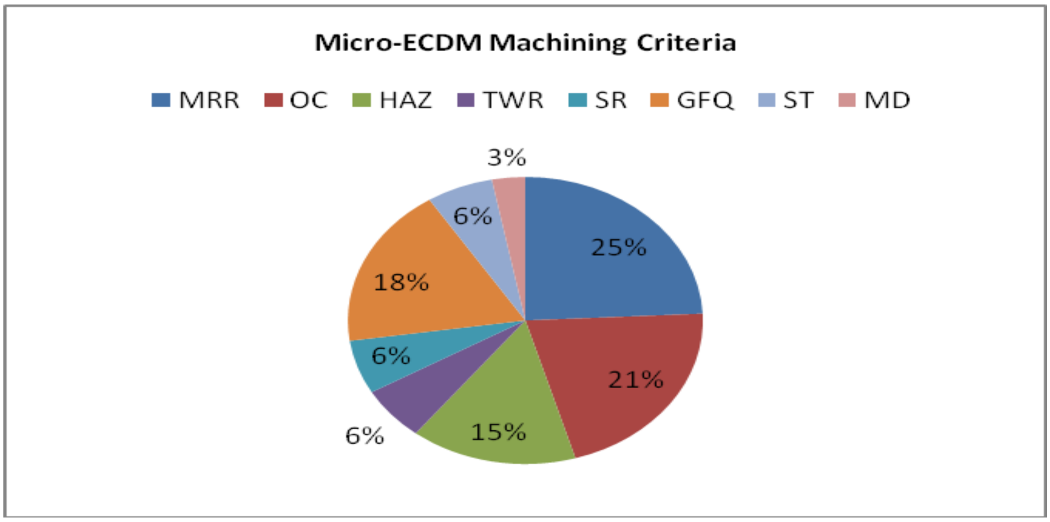


Fig.31 micro-ECDM machining criteria

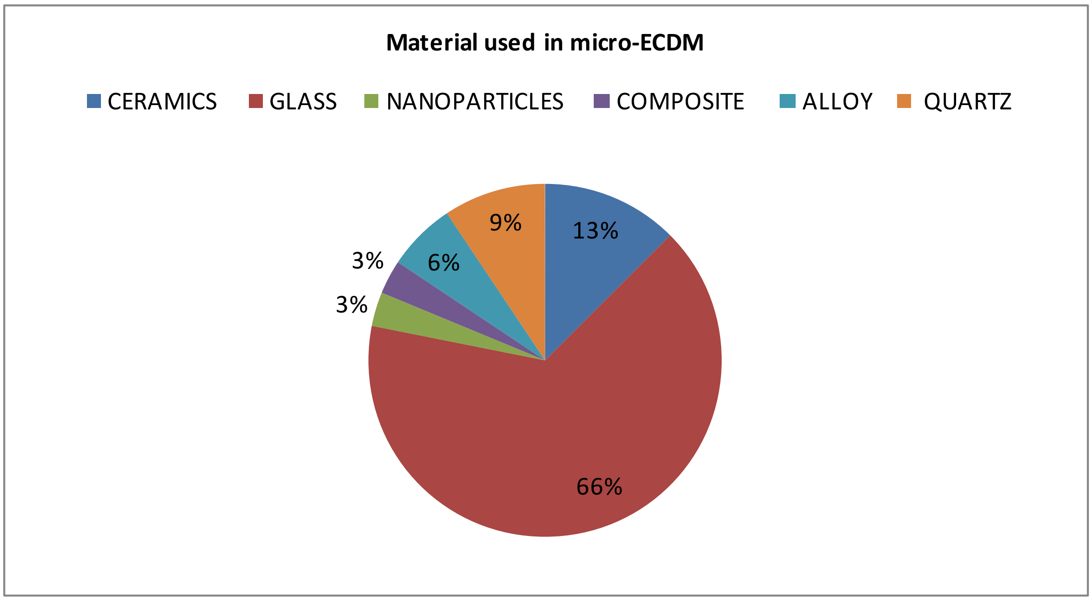


Fig. 32 material used in micro-ECDM