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Review of Electrochemical and Electrodischarge Machining

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Review of Electrochemical and Electrodischarge Machining

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Abstract

Electrochemical and electro-discharge machining processes are the two major electro-machining processes with unique capabilities. Electrical Discharge Machining (EDM) and Electrochemical Machining (ECM) offer a better alternative or sometimes the only alternative in generating accurate 3-D complex shaped macro, micro and nano features and components of difficult–to-machine materials. Technological advances reported in electrochemical and electro discharge machining processes, which reflect the state of the art in academic and industrial research and applications, are briefly reviewed in this paper.

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Keywords: ECM; EDM; electro-machining

1. Introduction

The demand for macro- and micro- products and components of difficult-to–machine materials such as tool steel, carbides, super alloys and titanium alloys has been rapidly increasing in automotive, aerospace, electronics, optics, medical devices and communications industries. In spite of their exceptional properties many of these difficult-to-machine materials seem to have limited applications. These materials pose many challenges to conventional machining processes (such as turning and milling). For example titanium alloys are susceptible to work hardening and its low thermal conductivity and higher chemical reactivity result in high cutting temperature and strong adhesion between the tool and work material leading to tool wear. Electrical Discharge Machining (EDM) and Electrochemical Machining (ECM) offer a better alternative or sometimes the only alternative in generating accurate 3-D complex shaped features and components of these difficult –to- machine materials. This paper presents a brief review of the state-of-the art research and developments in modeling, surface integrity, monitoring and control, tool material and tool wear and hybrid processes. Recent reports on emerging nano-scale electro machining are also reviewed. The second section describes the research activities in ECM. EDM research efforts are presented in third section. Nano electro machining (nano-EM) is briefly discussed in section four. The last sections provide summary and acknowledgements.

2. Electrochemical machining

Electrochemical machining (ECM) is a non-traditional machining process in which material is removed by the mechanism of anodic dissolution during an electrolysis process [1, 2]. A D.C. voltage (10-25 volts) is applied across the inter-electrode gap between pre-shaped cathode tool and an anode workpiece. The electrolyte (e.g. NaCl aqueous solution) flows at high speed (10-60 m/s) through the inter-electrode gap (0.1-0.6 mm). The current density is usually 20 to 200 Amperes per cm square. The anodic dissolution rate, which is governed by Faraday's laws of electrolysis, depends on the electrochemical properties of the metal, electrolyte properties and electric current/voltage supplied. ECM generates an approximate mirror image of the tool on the workpiece. Advantages of ECM over

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other traditional machining processes (e.g. turning and milling) include its applicability regardless of material hardness, no tool wear, comparable high material removal rate, smooth and bright surface, and the production of components of complex geometry with stress-free and crack-free surfaces [3]. Therefore, ECM has been applied in many industrial applications including turbine blades, engine castings, bearing cages, gears, dies and molds and surgical implants. A recently conducted study of technological and economical comparison of roughing operation of titanium and nickel based blisks by milling, EDM and ECM shows depending on the geometry, ECM is comparable in machining titanium alloy. EDM has been found to be a better alternative for smaller batch sizes whereas ECM is more suitable for large scale production [4]. The research and technological development activities in ECM process, its variants and related hybrid processes are continuing to address its emerging applications. Pulse electrochemical machining (PECM) is a variation of ECM where a pulsed power is used instead of DC current. PECM leads to higher machining accuracy, better process stability and suitability for control. These advantages are due to the improved electrolyte flow conditions in the inter-electrode gap, enhanced localization of anodic dissolution, and small and stable gaps found in PECM [5,6]. When applied for micromachining PECM is referred as pulse electrochemical micromachining (PECMM). ECM process mechanism has been used in developing a pulse/pulse reverse approach to electro-polishing and thorough-mask electro-etching with applications to automotive planetary gears, fluid control valves, medical stents and superconducting radio-frequency cavities [7]. As mentioned earlier ECM applications include aerospace [8, 9], biomedical [10, 11], deburring [12], energy [13-17], deep hole machining for automotive applications [18-20], and tribology [21].

2.1. ECM Process modeling, simulation and Tool Design

In ECM and its variant processes, it is essential to estimate the anode material removal thickness at a given time increment. The material removal thickness is a function of current density distribution at the gap including the varying electrical conductivity of the electrolyte. The electrolyte properties depend on the temperature and gas bubble formation, which in turn depend on the velocity and pressure fields besides current density. Therefore ECM modeling involves a set of mass, heat electric charge transfer equations [22]. The non-contact nature of ECM has resulted in the need for the modeling of the ECM process for the prediction of anodic profile. A review of the mass transfer issues in ECM with the problems associated with ECM processes is given in [23]. Numerical modeling of the ECM process considering the hydrodynamics involved in the process was studied in [24]. The end anode shape resulting after ECM using a triangular shaped cathode was modeled in this study. A similar model for curved cathode considering electrolyte condition over curved surfaces was modeled in [25]. Cathode design in die sinking ECM with shaped electrodes is important as the inverse shape of the cathode is obtained on the workpiece (anode). A convergence analysis on the performance of Finite Element Method (FEM) as a tool for cathode design modeling is given in [26]. For the Electrochemical finishing process the variation of gap, taking into account the pulse current was modeled in [27]. The model was for a rotating anode (workpiece) and stationary cathode. Apart from predicting the gap, the model predicts the surface roughness values after the finishing process is completed [27]. Simulation of the heat generated during the ECM process and its effective dissipation using electrolytic flow was studied in [28]. It was found that a hollow cathode and pulse voltages help in the effective control of the heat generated. Numerical simulation of the ECM process taking into account the temperature effects was studied in [29,30] and the temperature distribution was found to have an influence on the shape of the anode with regions of higher temperature showing higher machining rates. For better accuracy and simplification of tool design, a smaller gap size and a stable gap state (by reducing the non-uniformity of electrolyte conductivity) are required. Recently, it is shown that the dimensional accuracy and productivity of electrochemical shaping of airfoils can be enhanced by applying ECM followed by PECM [31].

2.2. Process control and monitoring

The inter-electrode gap is a critical parameter that needs to be controlled during the machining process in ECM and its variant processes. Setting and maintaining a small yet stable gap size in ECM is very important to achieve better dimensional accuracy and control. A trial and error approach was used in [32] to improve the machining accuracy of ECM process by adjusting the process parameters. Current and voltage signals are the basis for the gap monitoring in several of the control techniques used for ECM gap monitoring [33-36]. In one study the forces induced on the tool electrode due to the electrolyte was used as a measure of the inter-electrode gap [37]. Machine vision based gap monitoring was developed in [38] with gap control up to 200 µm. As ECM parameters and control are still largely dependent on the human operators' experience, expert systems automating the process are needed [22]. Some examples of expert systems currently implemented include artificial neural networks [39-41] and fuzzy logic controls [42, 43].

Micro ECM monitoring is based on voltage and current feedback signals from oscilloscopes [44] or current sensors [44-47]. The waveform observed during the process of ECM can be used to predict the MRR, hole accuracy and machining time [44]. Short circuit detection and prevention enabling better process stability and precise machining are further advantages from using in process control during micro ECM. Short circuits and sparks depend on the process parameters like machining voltage, pulse parameters and electrolyte concentration. Parametric optimization of these parameters can be used to machine with no spark affected zone (figure 1) [46].

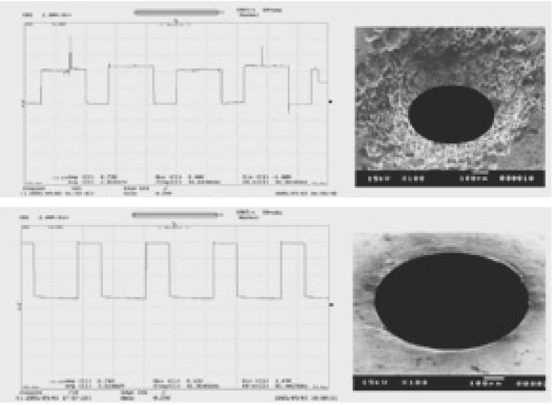


Fig. 1. Waveforms of (Top) Spark affected hole; (Bottom) No spark affect hole [46]

2.3. Process capabilities

ECM is capable of machining on a wide variety of conductive, hard to machine, engineering materials like metals [15, 48-50], semiconductors [51-53] and composites [46, 54-56]. Features as small as 0.5 µm can be machined using ECM (figure 2). The theoretical limit for the minimum gap width (precision) during ECM based on the charging time constant, and pulse limitations is estimated to be 20 nm [59]. Surface finish values as low as 100 nm can be achieved using electrochemical finishing techniques. [60]. A study of ECM generated surface characteristics of titanium revealed that higher rates of electrolyte flow resulted in improved material removal rate and better surface finish [9]. High aspect ratio microstructures with dimensions as small as 1 µm were fabricated on silicon for MEMS application using photo assisted ECM with HF electrolyte. The 4 step process uses photolithography, chemical etching and anisotropic electrochemical machining to machine highly dopes n-type silicon [51,58]. Other ECM process capable of machining silicon are wire ECM [61], laser assisted ECM [62], abrasive assisted ECM [63] and pulsed ECM [52]. When compared with milling and EDM, ECM is the most cost effective method for machining of Ti alloys [4].

Several studies have been conducted on the fabrication of microelectrodes using ECM [33, 54, 64-67]. Tool handling issues are minimized with the in process manufacturing of tools used in ECM. Ultra high aspect ratio micro tools (>450) were produced using pulsed ECM using reverse currents [50]. These tools can be used to machine high aspect ratio micro holes using ECM or EDM. These electrodes also find biomedical application as neural implants (figure 3) [10]. Surface finish achieved through this process was 0.3 µm. The surface roughness of micro tools was also improved with the use of ECM combined with a honing process to get very fine finish (Ra 0.02 µm). Wedge shaped tools with tip radius 0.6 µm were machined using the PECM process in [68]. These tools were then coated with diamond like layer for mechanical machining applications. Vibration assisted ECM of micro tools was studied in [69]. Micro tools with varying cone angles and reverse conical shapes were obtained with changes in vibration parameters of the process.

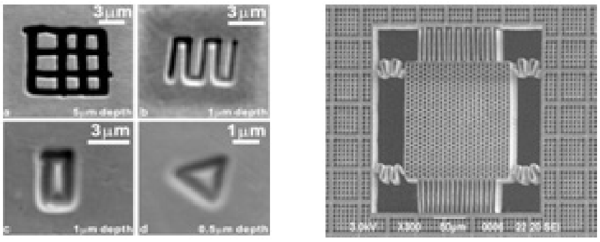


Fig. 2. (Left) Micro ECM on Au workpiece [57]; (Right) High aspect ratio microstructures on Silicon using ECM [58]

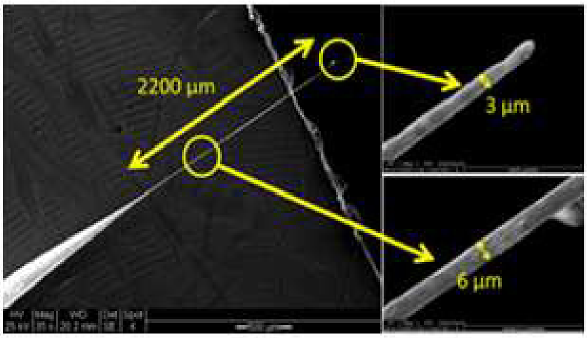


Fig. 3. High aspect ratio microelectrode [10]

Holes with complex internal structures and undercuts can be machined using ECM that are otherwise almost impossible to be machined using any other process (figure 4, 5) [13, 14, 70]. The non-contact nature of machining enables the drilling holes having an inclination of 40° using wedged shape electrodes [71].

Tools with spherical ends manufactured by a single discharge EDM process were found to produce holes with no taper [72].

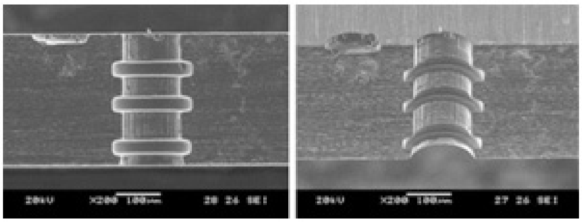


Fig. 4. Micro holes machined using ECM with grove array [70]

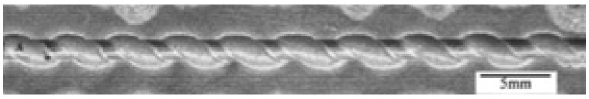


Fig. 5. Tabulator cooling hole with spiral duct [13]

2.4. Electrolytes

The electrolytes used in ECM depend on the type of material to be machined. Acidic, basic and neutral aqueous solutions have been used as electrolyte in ECM [73]. Dilute acidic solutions are preferred method for ECM of steel due to the solubility of the metal debris in to the electrolyte. Tungsten carbide composites are machined using alkaline and neutral solutions due to the formation of passive oxide layer in acidic solutions [46]. The choice of electrolyte is also known to influence the surface characteristics of the material being machined [73]. A non-aqueous electrolyte (NH_4NO_3/NH_3) was used in the ECM of Molybdenum as in aqueous electrolytes Mo forms complexes with OH^- ions [74]. The environmental concerns arising from the use of toxic electrolytes are one of the limiting factors in the widespread implementation of ECM in the industry. Environmentally friendly ECM using nontoxic electrolytes like water [8, 75] and citric acid [76] have been recently reported to establish ecofriendly micro ECM capabilities.

2.5. Tools

The tools used in ECM are of two types shaped and unshaped tools. The first variation is ECM sinking in steady state process. In this process the tool profile is a 3-D negative image of the required surface profile. The tool is allowed to sink in to the work piece at a constant feed rate until the required shape is obtained on the work piece. Another variation is the ECM shaping process. In this process a universal simple shaped tool (e.g. cylindrical or spherical) is moved along a specified path to obtain the required shape of the work piece. The major requirements for a material to be used as a tool in ECM are high electrical and thermal conductivity, corrosion resistance and rigidity to withstand the electrolytic flow. Common tool materials include platinum, titanium, tungsten, tungsten carbide and copper [77]. Tool design forms a major part of the modeling efforts of ECM process for the shaped tool ECM process [78]. Modeling of tool design based on a given workpiece geometry using FEM was reported in [79].

One of the major advantages of ECM is the scalability of the process with the use of multiple electrodes on the same machining setup. ECM using multiple electrodes machined to machine arrays of micro holes was studied in [80-82] (figure 6) resulting in increased productivity. Taper induced on the workpiece during ECM drilling is a major concern. Some of the tool designs for the reduction of taper include dual pole tools [83], insulated tools [84], and tools with shaped ends [72]. A simple procedure for the tool insulation with a 3 μm thick layer is given in [85]. Tungsten micro tools coated with nickel were shown to be more corrosion resistant and improve the machining rates during ECM [77]. In the shaped tube electrochemical machining (STEM) process acidic electrolyte is delivered through the tool electrode. This process is used in the drilling of cooling holes in turbines [20]. ECM using electrolyte flow generated through extraction (reverse of STEM) is reported in [86, 87] resulting in improved process stability and accuracy. Low frequency tool vibrations were found to improve machining rate and accuracy due to the enhancement in the electrolyte flow conditions [88]. A detailed analysis of the effects of tool geometry, electrolyte immersion depth, size and length on the machining rate, accuracy and gap size is given in [89].

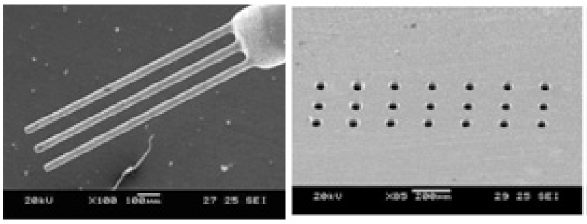


Fig. 6. Micro hole array fabricated using multiple electrodes [80]

Jet electrochemical machining (JECM) is a variation of ECM where the electrolyte is pumped through a nozzle to form a jet. DC power is supplied between the nozzle and the workpiece with the current being transferred by the jet electrolyte. Complicated shapes were machined with the motion to the nozzle [90, 91]. A flat electrolyte jet was used in [92] to produce micro milled surfaces and electrochemical turning applications (figure 7). The use of DC power was attributes to the higher machining rates when compared with pulsed ECM. Accuracy of ± 5 µm and structures with aspect ratios of 3 have been machined using JECM [93].

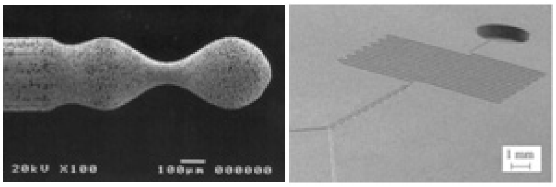


Fig. 7. JECM : (Left) Micro turning [92]; (Right) Micro reactor [93]

Electrochemical machining using wire electrodes (WECM), comparable to the wire EDM process, have been developed to machine high aspect ratio micro structures [94-99]. With the optimization of wire travel speed, feed rate, vibration and electrolyte flow rate high precision microstructures with aspect ratio 30 were produced as shown in figure 8 [95]. The wire electrode used in WECM can also be produced in situ using ECM. Wires with diameters as small as 6 µm were produced in situ in [98]. The wire used in WECM needs to be rigid enough to withstand the forces due to generated bubbles and inadvertent physical contact between tool and workpiece [94].

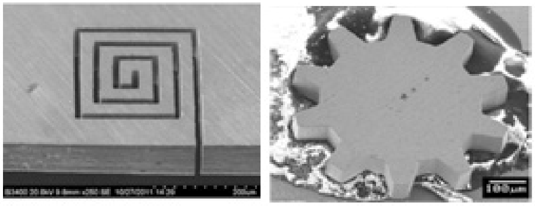


Fig. 8. WECM : (Left) Square helix [84]; (Right) micro gear [94]

2.6. Hybrid ECM

ECM has been combined with several other machining processes to enable improved machining characteristics. A hybrid machining center consisting of electro discharge machining (EDM), electrochemical machining (ECM) and mechanical milling was developed in [100]. The hybrid process integrated the advantages of each of the machining process to produce micro structures on difficult to cut carbides with lower residual stress, high efficiency and low surface roughness (<100 nm). Ultrasonic assisted electrochemical finishing process was studied and found to improve the surface finish when compared to regular electrochemical finishing [101].

The combination of EDM and ECM processes on the same setup is capable of generating highly complex and precise 3 dimensional structures [102]. Low resistivity deionized water which has the properties of a dielectric as well as a conductive fluid to some extent has been used to develop a process which involves simultaneous EDM and ECM. The process reduces the surface roughness giving a better surface finish (figure 9) [103, 104].

In Laser assisted ECM a laser beam is focused on an area exposed to the electrolyte jet, which dissolves a specific region improving precision and surface roughness. This process also reports a higher material removal rate due to temperature increase in the region targeted by the laser beam [105].

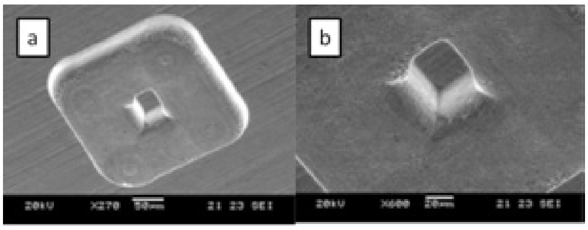


Fig. 9. Micro milling using a combination of ECM and EDM [104]

The machining precision decreases with increasing depth but can be improved by increasing the speed of the electrolyte jet [106]. It has been reported that the local temperature rise does not cause any thermal damage and so the machined surface is free of stress [107]. This process has the capability to generate complex 3 dimensional patterns like micro-stents [108].

In abrasive ECM, abrasives like silicon carbide are suspended freely in the electrolyte in the vicinity of the work piece. These abrasives along with a wire cathode are responsible for slicing silicon wafers with better production rate, less cost and good surface integrity [63]. Abrasive electrochemical grinding using resin-bonded wheels have been reported, however, the deficiencies of the process like wheel wear still remain a challenge [109]. Electrochemical grinding has been used to machine small holes with sharp edges. The process involves coating the tool electrode with abrasives and rotating it at high speed. Initially material is removed through the action of ECM and then the holes are ground for better finish through contact machining [110].

Ultrasonic electrochemical machining involves vibrating the tool electrode to agitate the abrasives suspended in the electrolyte for a good surface finish. A study of the geometry and type of the electrode which gives a well-polished surface is reported and the effect of ultrasonic energy is acknowledged [101]. This energy is also responsible for the removal of debris from the machining zone and creation of optimal hydrodynamic conditions affecting the surface layer [111]. The use of magnetic as well as ultrasonic energy has been reported to remove sludge out of the electrode gap. The process gives a very good surface finish in smaller time [112].

An extensive review of hybrid machining technologies with ECM as either a primary or one of the constituent processes has been reported in [113] with a special emphasis on interactions among the participating processes. A theoretical model and experimental verification for optimizing the performance of electrochemical discharge machining process and comparison of resulting surface quality with EDM milling are presented in [114]. Recently, precision machining of small holes of diameters 0.6 mm with sharp edges and without burrs been demonstrated in [115]. A hybrid process involving micro-milling and electrochemical turning using a flat electrolyte jet has shown to generate accurate, complex micro patterns in metallic sheets and rods in [116].

3. Electro discharge machining

Electro Discharge Machining (EDM) is a non-contact electro-thermal machining process. Precise machining can be done on electrically conductive and semi-conductive materials using this unconventional machining process. EDM can be used to drill circular and non-circular holes, generate profiles and make complex shaped dies of both macro and micro sizes. Both the micro EDM and the micro EDM have great potential and research work is going on in this field to improve the machining process and equipment. Recently a related process, electro machining at the nano scale has been reported.

3.1. Process mechanism

EDM is a thermo-electric machining process in which the material removed or eroded from the work piece due to the energy from a series of electric discharges generated between the tool electrode and the work piece electrode immersed in a dielectric medium. The electric discharges or sparks produced at the gap remove the work as well as tool material by melting and evaporation. The dielectric medium acts as a deionizing medium between the electrode and the work piece, thus providing the optimal conditions for spark generation and also flushes the debris formed in the spark gap [117,118]. The erosion mechanism in EDM is a very complex phenomenon and involves many physical processes. Therefore, the exact physical phenomenon taking place in the spark gap (gap between the electrode and work piece) continues to be a topic of research [117,118]. Molecular dynamics simulation of the process shown in figure 10 reveals that the material removal mechanism can be explained by two ways; one by vaporization and the other by the bubble explosion of superheated metal. It was also observed that the material removal efficiency is between 0.2 and 0.5 owing to the resolidification of the melted material pool [119].

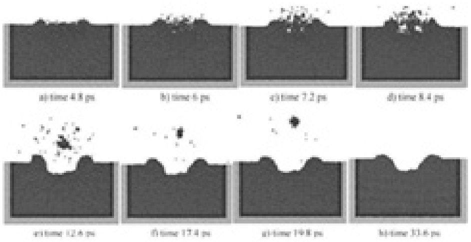


Fig. 10. Material removal process of electrode [119]

3.2. Power supply

With improved response characteristics power transistor circuit having large current handling capacity replaced the relaxation type power supply initially used in EDM. However, the relaxation type pulse generators are still used for finishing process because short pulse duration with constant pulse energy is difficult to obtain in transistor type pulse generator [118]. A transistor controlled RC type fine finish power supply using anti electrolysis CPLD based pulse control circuit is reported in [120]. This equipment can achieve a fine surface finish of 0.22 µm Ra. Experimental comparison between RC type pulse generator and transistor type pulse generator on tungsten carbide has been provided in [121]. In a twin electrode machining system, transistor type pulse generator and RC pulse generator have been used for rough machining and finishing respectively (figure 11).

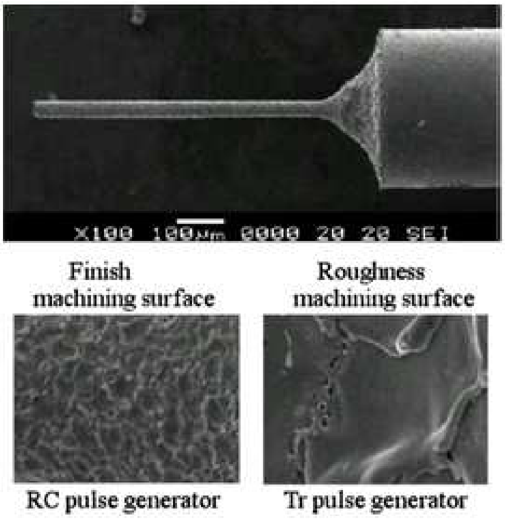


Fig.11. View of micro electrode tool machining by the twin-wire EDM system [122].

3.3. Gap monitoring and control

The gap between the electrode and the work material (spark gap) should be monitored to avoid short circuit, open circuit or arcing. The presence of left over debris due to either short pulse off-time and/or insufficient flushing can change the electrical conductivity at the gap and may result in non-uniform and unstable discharge process. These developments lead to arcing and unstable machining which results in damage to work piece and tool and adversely affects the process performance. Therefore, extensive research and developments efforts have been reported in the field of monitoring and control of EDM process over last few decades. The prediction of on-set of arcing based on the collection and, modeling and analysis of gap voltage and/or current signal and follow-up corrective actions based on the control modeling and hardware has been the main objective of these efforts [123-127]. The conventional control system monitors the gap voltage and retracts the electrode along the direction of the command trajectory. Recently, wavelet transform method has been applied to monitor EDM gap discharge status [128]. A pulse discriminator for linear motors equipped EDM and control strategy for high efficiency deep-hole drilling is proposed in [129]. A quick retract method of control is reported to have 30% increase in the material removal rate without affecting the efficiency and surface roughness [130].

3.4. Electrode

High conductivity, heat resistance and high melting point are the main desired properties for an EDM tool. The most common materials used in EDM tooling are copper, graphite, tungsten and tungsten carbide. Research is being done on many new materials including composites for EDM tooling. A ZrB_2-Cu tool was developed and tested. This composite showed higher material removal rate (MRR) and lesser tool wear rate (TWR) as compared to copper but had some shortcomings in average surface roughness and over-cut. [131]. To avoid damage on the electrode of micro EDM and also to handle the tool with ease a ‘peeling’ tool is proposed. Zinc is electroplated on a tungsten core. With a single discharge the zinc coating ‘peels’ off, exposing the tungsten. Another advantage of using a peeling electrode is that when the core becomes worn out and short the removal of the coating can be repeated by another discharge to expose fresh electrode. [132]. To improve the uniformity and stability, a collection very small tubes called “bunched electrode” can provide higher MRR and also better flushing. A bunched electrode is formed by bunching a number of hollow celled electrodes with an end contour as required in the die (in case of die sinking EDM). With bunched electrodes it is possible to apply a higher peak current and hence higher MMR can be achieved [133,134].

3.5. Dielectric medium and flushing

A suitable dielectric for EDM should be able to provide suitable conditions for initiation and maintenance of good effective electric discharges, cool the electrodes and to carry away the debris from the spark gap (flushing). The most common dielectric mediums used are hydrocarbon oils such as Kerosene. In wire-EDM deionized water is used. Distilled water has also been used for some special applications. In air assisted water EDM air and water act as the dielectric medium. There are two nozzles, one for tap water and the other for compressed air near the spark gap. When machining is done the gas-water mixture acts as the dielectric medium. [135]. This process has the potential to significantly reduce environmental pollution. Powder mixed dielectric has been shown to improve surface finish for large area dies. Recently powder mixed near dry EDM uses (PMND-EDM) uses powder, gas and liquid as a 3-phase dielectric and this process is found to give a higher MMR owing to the larger energy density in discharge channel [136]. Dry EDM process is used to machine carbon nano fibres (CNF) for improving the uniformity of the field emission (figure 12). Dielectric medium is not used in this process to avoid contamination. Instead a high speed jet of gas is used as the dielectric medium [137].

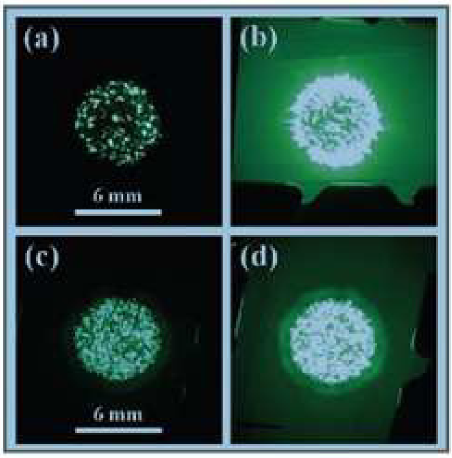


Fig. 12. Emission Images at a low electric field range: (a), (b) before and (c), (d) after the EDM treatment [137].

3.6. Surface integrity

Surface integrity is one of the most important issues with EDM. Discharge pulse energy is one of the important factors that affect surface integrity. The surface roughness of the material increases with the increase in current and voltage. The crater size varies with pulse energy though it also depends on the material properties. The thermal action in EDM may cause micro cracks, induces residual stresses, and changes the micro hardness of the sub-surface and surface layers, results in carbon and hydrogen diffusion. Extensive studies have been reported on EDM surface integrity in last 2 or 3 decades [138-141]. In a recently reported study on the feasibility of using Wire-EDM for potential applications in aerospace, it was found that employing ultra high frequency/short duration pulses result in extremely low level of workpiece damage [142]. The recast layer formed can be removed by using gentle or finish machining condition or electrochemical process or precision grinding. In the study of surface integrity properties of Al_2O_3 composite machined by EDM, it was concluded that surface roughness increases with discharge current and pulse-on time. But by carefully selecting the EDM parameters materials can be machined without any significant loss to surface integrity [143]. Recent study of a comprehensive comparison on surface integrity (surface finish, microstructure, micro hardness and residual stress) using CH- and water-based dielectrics in Wire EDM reveals that surface roughness of close to 0.1 micron and very thin rim zone of less than 0.3 micron can be obtained [144]. Zn-coated wire electrode along with an optimized machining technology adequate surface integrity can be obtained in machining titanium alloys [145]. A comparative study of fatigue strength and other surface integrity aspects generated by grinding and Wire EDM of titanium alloy 9 Ti-6Al-4V was recently reported in [146] with a conclusion that a standard Wire-EDM process with instabilities has a better fatigue life than a standard grinding process adjusted for a good looking surface.

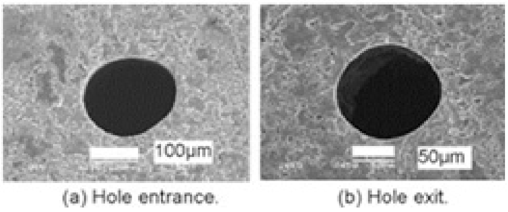
3.7Micro-EDM

Extensive research and development efforts have been reported in the EDM literature for the last 2 decades. Comprehensive reviews of physical and chemical machining processes including Micro-EDM and Micro-ECM have been presented in [147-148]. Besides process mechanism, surface integrity and sensing and control, tooling and tool wear in micro-EDM continue to be an important topic of research. Tungsten having a high melting point and tensile strength is the predominant material in micro-EDM [149,150]. Tungsten carbide and copper have also been used as tool material in micro-EDM [151-152].

Tool wear in micro-EDM is significantly affected by polarity and thermal properties of electrode material [118]. The boiling point in addition to the melting point of the electrode material plays an important role in micro-EDM tool wear process [153]. The suggested EDM micro EDM tool wear compensation techniques include the linear compensation and uniform wear method [154-157].

3.8 Hybrid EDM and Extended process capabilities

An application of vibration including vibrations at ultrasonic frequency to maintain uniformity and stability at the gap by providing an extra motion to dielectric and generated debris has been an important topic of research. A combination of ultrasonic vibrations and planetary tool movement generates micro holes with aspect ratio as high as 29 (figure 13) [158].



(a) Hole entrance. (b) Hole exit.

Fig. 13. Micro-hole (a) Entrance (b) Exit [1158]

Micro milling by EDM has been used to fabricate micro components with complex shapes shown in figure 14 [159]. A micro array with an aspect ratio of 33 shown in figure 15 has been machined by reverse-EDM [160].

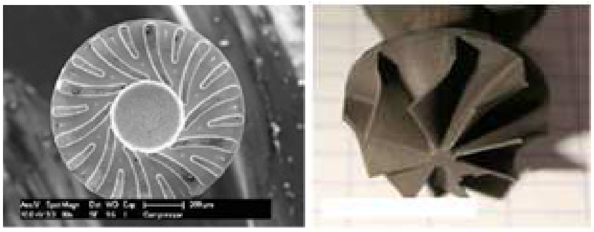

A micro-compressor on a Ø 1 mm cylinder Turbine impeller

Fig. 14.: Micro components made by EDM-milling [159]

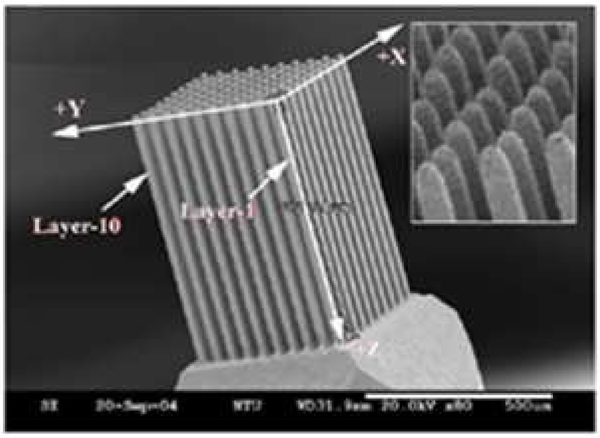


Fig. 15 SEM micrograph of a micro array made by reverse-EDM process [160]

EDM has also been used to produce medical devices. EDM was successfully used to machine a magnesium alloy WE43, a bio-compatible material [161]. A micro ball joint made by EDM is shown in figure 16. The diameter of the rod and the ball are 100 µm and 290 µm respectively and they are made by WEDM. The socket is fabricated by electroforming method [162].

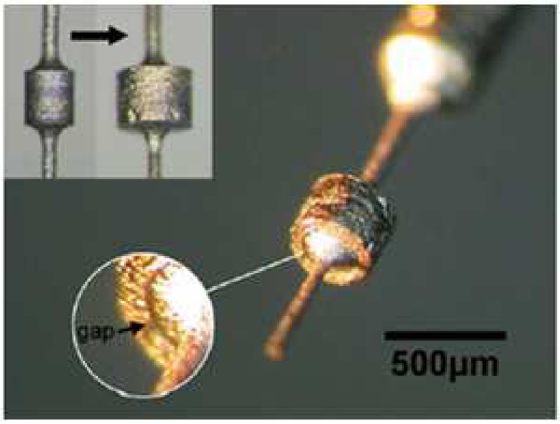


Fig. 16. A micro ball joint[162].

4. Nano Electro Machining (nano-EM)

In a recently introduced machining technique at the nano scale called nano Electro machining (nano-EM), an atomically sharp electrode tool immersed in an organic oil medium is used to generate sub-15 nm scale features on hydrogen flame annealed atomically flat gold film (Figure 17).

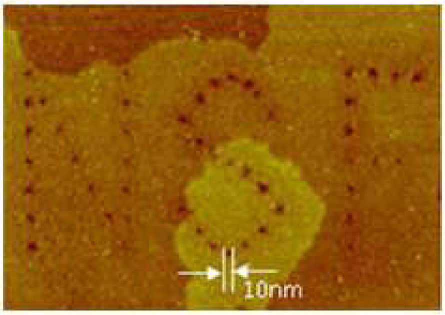


Figure 17 : STM analysis of nano-holes to analyze the morphology and measure diameter of holes

A scanning tunneling microscope (STM) is used to carry out the process [163]. It was found that upon machining the tool tip end radius was sharper and the tool surface was modified to a nanocrystalline matrix of tungsten oxide and tungsten carbide which are expected to extend the tool life (Figure 18) [164]. Modifications occur as a result of only the electric field.

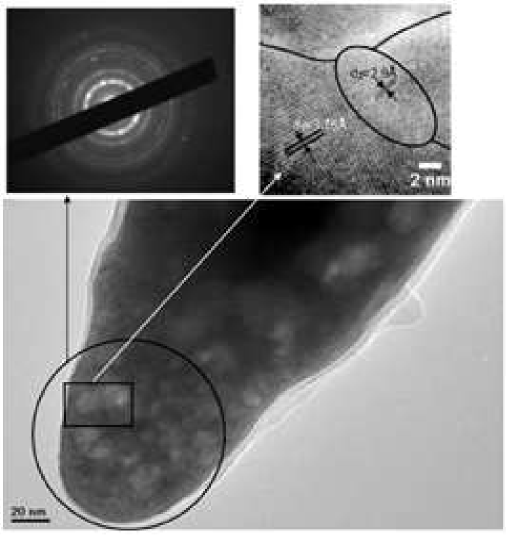


Figure 18 : Nano-EM tool gets covered with a protective and conducting layer of nanocrystalline WO_3, C, W and WC.

Nano-EM has also been carried out in atmospheric air using STM as the platform and an in-situ process of evaluating the tool quality before and after machining has been used by monitoring current-displacement (I-Z) spectroscopy curves. The related experimental results show that this dry nano-EM is capable of generating consistent nano-features with good repeatability [165]. A feasibility study of fabricating nano-holes on graphene conducted recently has shown that nano-EM is capable of fabricating 3-4 nm size features with visible atomic arrangement of carbon in graphene [166]. A pulse generator reported in [167] for nano-EDM uses a coupling method in which the pulse generator is coupled to the tool electrode by a capacitor. This coupling leads to energy minimization to accomplish nano-EDM.

5. Summary

Recent advancements in various aspects of electrochemical and electro-discharge machining that reflect the state of the art in these processes are presented in this paper. ECM and EDM technologies have been successfully adapted to produce macro, micro components with complex features and high aspect ratios for biomedical and other applications. These processes are also being attempted at the nano-scale.

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