MICRO-EDM: SYSTEM AND ITS APPLICATIONS*

(**Presented at m^nf2013, 1^st National Conference on Micro and Nano Fabrication, January 21-23, 2013, CMTI, Bangalore*)

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Abstract: *Micro-EDM, a non-conventional machining process, is one of the most promising tool based micromachining technique which has the capability to machine micro-components with almost negligible amount of cutting force. Recent applications of micro-EDM process are increasing at an impressive rate and an explicit outcome of multidisciplinary research effort on the subject matter. This paper presents an overview of micro-EDM technology and some of the recent applications.*

Keywords: *Micro-EDM, Tool-Based Micromachining, Compound Micromachining, Multi-Process Micromachining*

1. INTRODUCTION

Micro-EDM is a material removal process employing discharges between a workpiece and a micro-scale electrode in a dielectric fluid. Discharges occur when the electric field between the electrode and workpiece exceeds a critical value and the dielectric breaks down. Either increasing the electric potential or reducing the separation distance between the electrode and workpiece may cause the field to exceed the critical value. Energy from each discharge melts a microscopic amount of material, which is subsequently flushed away after the voltage drops and the discharge collapses [1–3].

Even though micro-EDM is based on the same physical principle of spark erosion it is not merely an adoption of EDM process for machining at micron level. There are significant differences in the size of the tool used, machining method of micro-sized tools, the power supply of discharge energy, movement resolution of machine tool's axes, gap control, flushing techniques, and also in the processing techniques [3,4]. For example, the terms micro-EDM milling, Wire Electro-Discharge Grinding (WEDG), repetitive pattern transfer which forms a considerable amount of the basis of micro-EDM process but specific to micro-EDM process alone and not required for conventional EDM process.

Literatures available at public domain have shown significant contributions to micro-EDM going back 40 years. In 1968, Kurafuji and Masuzawa [6], demonstrated the first application of micro-EDM. Through the years, micro-EDM has been developed into a versatile tool for fabricating a variety of micro-mechanical components, molds for plastic injection molding, sensors, micro-pumps, micro-nozzles, micro-grippers [7–14]. Micro-EDM is suitable for these and similar applications because of its remarkable advantage of low machining force as molten or vaporized material can be removed without direct contact. This property provides advantages to both the tool and the workpiece as probable deformation by machining force is avoided. Another very important advantage of micro-EDM process is the capability of repetitive pattern transfer, which will be discussed in the following sections of this article. This process is capable of fabricating very complex micro-structures by series of pattern transfer cycles.

With growing trends towards miniaturization of machined parts, developments in the area of micro-electromechanical systems (MEMS), and requirements for micro-features in difficult-to-cut materials, micro-EDM has become an important and cost-effective manufacturing process due to its non-contact machining capability by micro-sized tools. Promising applications are not just limited to the machining of hard materials for micro-moulds, but also the production of difficult-to-make features such as fuelinjection nozzles, spinneret holes for synthetic fibres, electronic and optical devices, micro-mechatronic actuator parts and micro-tools for producing these devices [15].

Current micro-EDM technologies used for manufacturing micro-features can be categorized into four major types [3]: (a)micro-wire EDM, where a wire of diameter down to 0.02mm is used to cut through a conductive workpiece, (b) die-sinking micro-EDM,where an electrode with micro-features is employed to produce its inverted image in the workpiece, (c) micro-EDM drilling, where micro-electrodes of diameters down to 5μm are used to drill micro-holes in the workpiece, and (d) micro-EDM milling, where micro-electrodes are employed to produce 3D cavities by adopting a movement strategy similar to that in milling. There exists another important variant of the micro-EDM process practically very similar to WEDM with apparent grinding-like setup and is known as EDG. Masuzawa et al. [16] was the first to propose a variant of EDG using running wire (WEDG). The workpiece electrode is machined by feeding downwards against a traveling sacrificial wire. This process has been extended to the use of sacrificial block andsacrificial disk for EDG process [2,17,18] and has found extensive applications in tool fabrication [19].

This paper begins with providing a brief overview on physical principles of micro-EDM process, followed by a discussion on few of the most critical parameters that govern the underlying physical process in micro-EDM. Finally, this paper presents some of the recent novel processes and applications using micro-EDM.

2. MICRO-EDM PROCESS PHYSICS

Micro-EDM is the process of machining electrically conductive materials by using precisely controlled sparks resulting in plasma between an electrode and a workpiece. Plasma in micro-EDM process is generated by an electric breakdown in the gap space filled with dielectric under a condition when the electric field strength exceeds the dielectric strength of the dielectric; and finally this ignition process leads to a subsequent current flow that generates an electric discharge. Usually in EDM process a direct current (DC) voltage is applied to the electrode system, namely electrode and workpiece consisting of parallel plates of area defined by the commonarea on both the electrodes facing each other across a couple of microns gap. The machining process is driven by assigned and controlled gap, voltage, energy and frequency of discharge. High frequencies (>200 Hz) and small energies (10^{-6} - 10^{-7} J) for every discharge (40~100V) are required to obtain high accuracy and good surface qualities (roughness of about 0.1 μm). The discharge energy is supplied by a pulse generator and a servo system is employed to ensure that the electrode moves at a proper rate to maintain the right spark gap, and to retract the electrode if short-circuiting occurs. A dielectric circulation unit with pump, filter and tank is used to supply the fresh dielectric in the gap and to maintain the proper flushing out of debris.

2.1 Discharge in Micro-EDM

The sparking phenomena of micro-EDM can be differentiated into three important phases named as preparation phase for ignition, phase of discharge and interval phase between discharges [20]. When the gap voltage is applied, the two parallel electrode plates across which the EDM plasma forms is shown in Figure 1 [21] where due to a very high electric field strength initially a weakly-ionized channel forms which then rapidly grows from one electrode to the other and results in primary electron avalanche starting from the cathode. Subsequently this forms a streamer as the initiation of a discharge process as could be seen in Figure 2 [22,23].

During the discharge process the electrons will have thermal energy of a few eV to bring atoms into excited states and from the collision process dielectric molecules gets dissociated which finally forms plasma to conduct current with very high current density. Even though the usual RC based

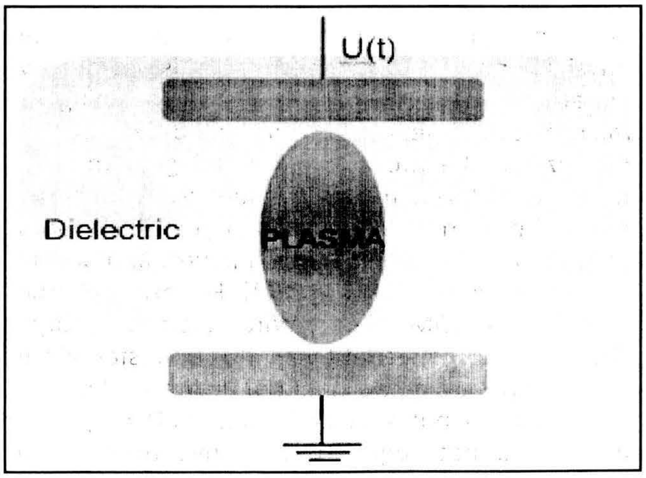

Fig 1. Parallel Plate Model of Micro-EDM Plasma

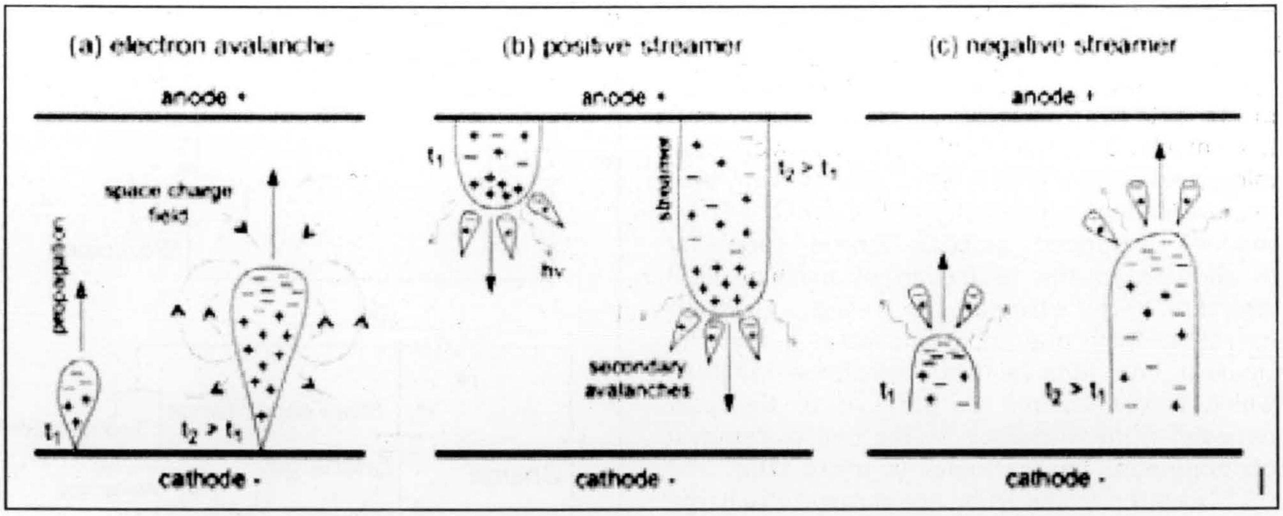

Fig 2. Breakdown Mechanisms Leading to a Spark Discharge. Propagation of: (a) the Primary Electron Avalanche; (b) a Positive Streamer; (c) a Negative Streamer [23,25]

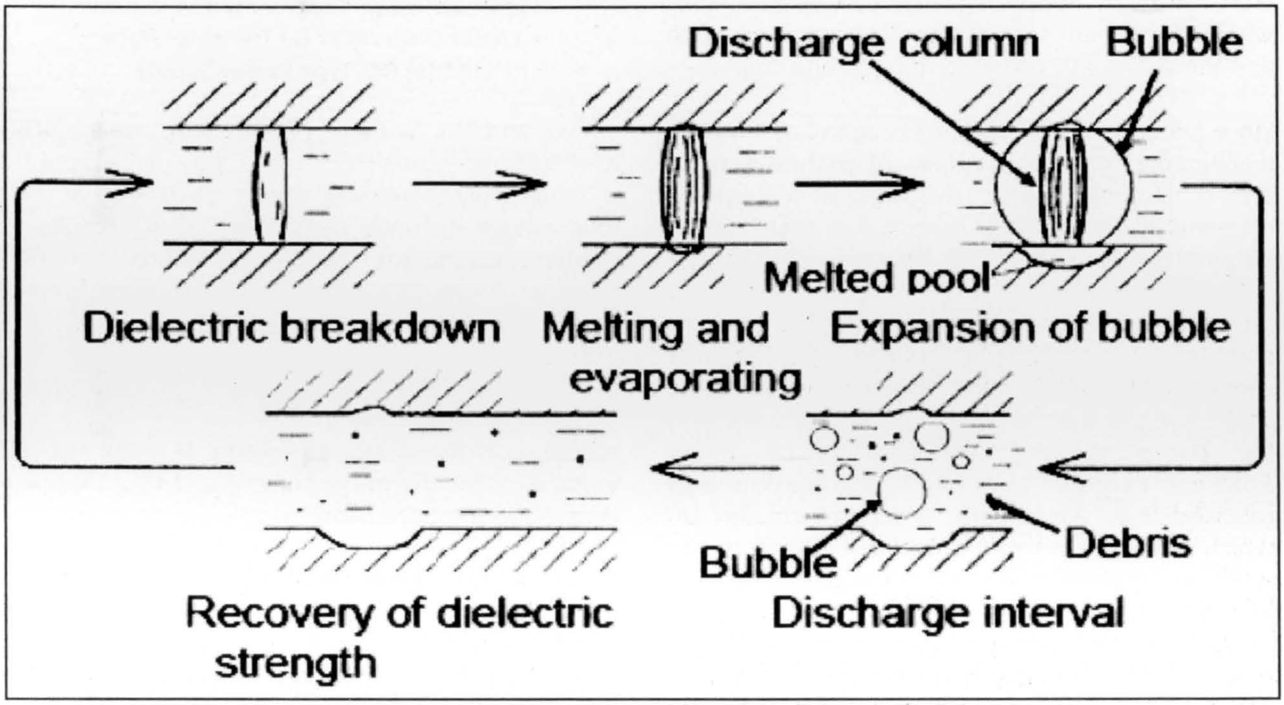

Fig 3. Model of EDM Discharge Phases Following a Dielectric Breakdown [26]

micro-EDM circuit is powered by a constant DC power supply, the presence of the large series resistor limits the current flowing into the channel. Most of the power dissipated in the plasma is supplied by the capacitor placed in parallel to the plasma and therefore micro-EDM discharge can be compared to the commonly used capacitive discharges in plasma engineering [24] as opposed to other type of discharge known as inductively coupled plasma discharge where the electric field is generated by a time-varying magnetic field of transformer action.

Material in the area struck by the spark melts quickly and may even vaporize. When the current at this point is switched off, which is during the pulse interval or during the charging cycle of capacitor, the heat source is thereby eliminated and the sheath of vapor around the spark implodes. Its collapse creates a void or vacuum and draws in fresh dielectric fluid to flush away debris and cool the area. Also the re-ionization happens which provides favorable condition for the next spark. Figure 3 illustrates the physical principle and gap phenomena during the micro-EDM process.

2.2 Micro-EDM Power Supply

While precision, rigidity and repeatability of machine tool structure are the cardinal factors from machine tools point of view for conventional micromachining processes, non-conventional micromachining processes, like micro-EDM, requires advanced process control capability in addition to the perfection of machine tool structure. For example, to realize precision micromachining one important factor is that the smallest unit removal (UR) should be minimal, which is the volume or the size of the part removed from workpiece by the unit of removal phenomenon. For example, in micro-EDM, the UR is a crater produced by one pulse of discharge which is a kind of quanta [5, 27] and to minimize the UR in micro-EDM the pulse shape needs to be controlled such that less energy is discharged in every pulse as opposed to the cutting processes where the UR consists of depth of cut, feed pitch and the cut length corresponding to one chip.

Since UR controls the surface roughness, smallest machinable feature, accuracy of feature control and machining quality, the amount of energy released in every spark determines such output parameters in micro-EDM. The troubling fact is that the UR of micro-EDM is comparatively rather big but cutting force is very small due to non-contact machining and on the other hand for conventional microcutting the UR can be quite small but the cutting force is comparatively very big. Therefore, for micromachining by micro-EDM it is essential to minimize the spark energy released from each spark to achieve smaller UR which will result in smaller machinable feature size and finer surface roughness. In addition to that, it is also important to maintain high machining throughput and the problem in micro-EDM is that the UR frequency is more of a quantum in nature which can vary significantly due to the sparking condition as opposed to the more of continuous UR frequency in conventional cutting process defined by the continuous feed rate.

There are two major types of micro-EDM power supply, namely Resistance-Capacitance (RC) or Relaxation type and Transistor type power supply (Figure 4), The RC based power supply has found widespread applications in micro-EDM, and is somewhat a rebirth after being replaced by transistor type power supply for conventional EDM power supply [10,26,28–33]. In transistor type power supply the discharge energy in every spark is controlled by the resistance across the circuit and the voltage (V and R in Figure 4(a)) and UR in transistor type power supply is minimized by increasing the resistance as at very low voltage settings (less than 60 V) results in unstable discharges [10]. Spark energy obtained from a single spark in transistor type power supply is given by equation 1 [34].

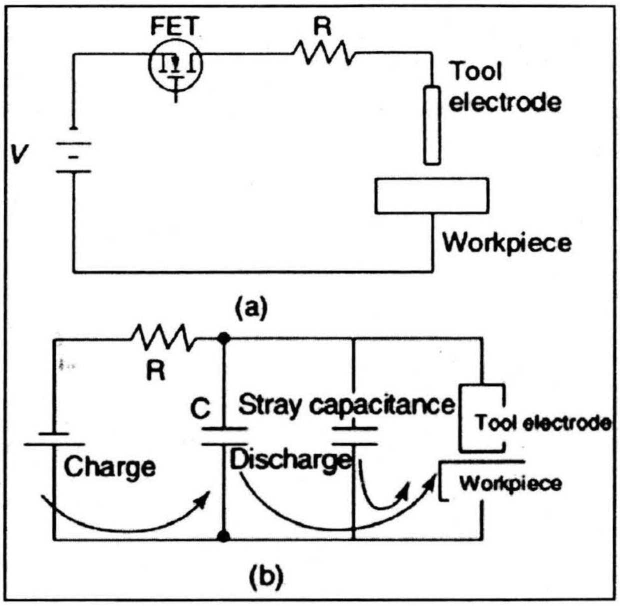

Fig 4. Schematic Representation of Basic Circuit Diagram of (a) Transistor-Type and (b) RC -Type Power Supply

$$E_d = ViT_{on} \qquad (1)$$

where, E_d is the discharge energy, V is the applied voltage, i is the discharge current and T_{on} is thepulse on time of the transistor.

In an RC or relaxation-type circuit, discharge pulse duration is dominated by the capacitance of the capacitor and the inductance of the wire connecting the capacitor to the workpiece and the workpiece to the tool, [15, 35] and the discharge energy is determined by the used capacitance and applied voltage. In the case of typical RC type power supply shown in Figure 4(b), the repetition of the charging discharging occurs in which capacitor C is charged through resistor R and discharged between the electrode and workpiece produces an extremely short width pulse discharge. The pulse energy E_d induced in the gap is calculated by using the formula of equation 2 [27,32], assuming that the gap voltage V_g is constant during the discharge.

$$E_d = 2CV_g(V - V_g) \qquad (2)$$

where, C is the discharge capacitance and V is the supplied DC voltage. When $V=2V_g$, the discharge energy is the maximum $1/2CV^2$, which is equal to the energy stored in the capacitor. For a more realistic case, the RC type pulse supply will also have stray capacitance contributed by the electric feeder, the tool electrode holder and work table, and between the tool electrode and workpiece. The stray capacitance contributes in parallel to the installed capacitor and equation 3 gets modified to the following equation:

$$E_d = 2(C_1+C_2)V_g(V-V_g) \tag{3}$$

where, C1 is the stray capacitance and C2 is the installed capacitance. This means the minimum achievable discharge energy per pulse is determined by the stray capacitance when C1 is set to 0. Thus in order to reduce the pulse energy, it is important to reduce the stray capacitance between the wire and the workpiece. Stray capacitance can be estimated by integrating the area under the voltage and current waveform or by extrapolating the capacitance value for discharge current pulse width at stray capacitance [36,37].

Equation 3 depicts the minimum achievable discharge energy per pulse is determined by the stray capacitance (C2) when discharge capacitance (C1) is set to 0, and thus in order to reduce the pulse energy, it is important to reduce the stray capacitance between the wire and the workpiece.In the final finishing or while machining features at the lower boundary of micromachining domain [38] a minimum discharge energy is necessary, and the capacitor is then not wired and machining is conducted with the stray capacitance only [15]. It can easily generate pulses with high peak current values and short duration, allowing efficient and accurate material removal, and meanwhile achieving the required surface quality. On a carefully designed equipment, the stray capacitance could be minimized to as small as 10~12pF, delivering 0.2mA peak current and 30ns wide pulse with discharge energy ~25nJ [39,40].

The frequency of discharge (discharge repetition rate) depends upon the charging time which is decided by the resistor (R) used in the circuit and this provides for one additional advantage of RC power supply, as when capacitance is reduced the capacitor charging up time is reduced following first order differential equation. The time taken for full charging up of a capacitor is given by 5 x RC and for the case of R = 1KΩ and C = 10pF full charging time of the capacitor would only be around 50 ns. Therefore, "R" should not be made very low because arcing phenomenon can occur instead of sparking and a critical resistance is desirable which will prevent arcing [4].

While RC type power supply has the potential to provide extremely high frequency of pulse rate with discharge energy as small as provided by the stray capacitance alone, it has quite a number of disadvantages compared to transistor type power supply [28,30]. While extremely low discharge energy is expected from the power supply during finishing condition, high discharge energy and faster machining rate for rough cut is expected. On RC circuit, discharge energy by increase in capacitance value and discharge frequency has inversely proportional relationship. This is mainly due to the reason that when capacitance is increased to increase discharge energy, the charging up time of capacitor becomes higher thus minimizing discharge frequency (as more time is needed for the circuit before the next spark can occur). However, for most micro-EDM application, the material to be removed is generally much smaller compared to the requirement of large material removal amount for conventional EDM. Another problem is - uniform surface finish is difficult to obtain because the dielectric breakdown can occur at any stage and during the capacitor charging up phase if a suitable condition is produced a half charged capacitor can discharge as well. This causes variable discharge energy and results in different crater size and variable surface roughness [26]. Thermal damage occurs easily on the workpiece if the dielectric strength is not recovered after the previous discharge and the current continues to flow through the same plasma channel in the gap without charging the capacitor [41].

On the other hand, the transistor type power supply is widely used in conventional EDM where UR can be much higher and provides much higher MRR as there is no need to charge any capacitor. The pulse duration and discharge current can be arbitrarily changed depending on the machining characteristics required and can provide for very uniform pulse shape resulting in much better control of surface roughness. One option for design of the transistor based power supply for lower energy settings can be done by employing high speed transistor to reduce pulse ON time which will also pave for higher discharge bandwidth by minimizing the OFF time and at the same time ensure discharges with equal discharge duration.

By using a transistor capable of providing 10ns ON/OFF time the discharge energy can be minimized to 560nJ. But, this is probably the best achievable case as increasing the resistor significantly more than 100Ω will reduce the peak current.For instance, using a 2kΩ resistor will allow for reduction of pulse discharge energy by another 20 fold reducing the discharge energy to the expected range around 28nJ but practically this will also reduce the peak current to 37.5mA which may not be even sufficient for holding the plasma in spark phase.

On the contrary, with the same amount of discharge energy one with higher peak current and short time width will have higher proportion of material removed by vaporization compared to a pulse with smaller peak current but larger pulse width which can be explained by considering a disk heat source based electro-thermal model [42,43]. Over longer spark duration but with the same amount of energy delivered – there is sufficient time for the heat to get conducted and proportion of material removal by melting action is higher compared to vaporization.

On the other hand with very short pulse there is rather less time for heat conduction through workpiece.Due to higher energy density (as the width is smaller, but the energy is equal) there is more energy to raise temperature as well as to provide for the extra energy needed for latent heat of vaporization, thus increasing the proportion of removal by vaporization. Higher proportion of material removal by vaporization is preferred as that will have less solid debris, less re-solidification and smaller crust layer. Therefore, the choice remains to use RC-based power supply for extremely small discharge with present state of design options using transistor-based micro-EDM power supply.

3. MICRO-EDM CONTROL PARAMETERS

3.1 Discharge Waveform and Energy

The pulse shape and discharge energy for micro-EDM can be determined from its electrical and discharge parameters. The higher the discharge energy, the higher will be MRR. However, with increasing discharge energy the relative electrode wear also increases and surface finish deteriorates.For RC power supply (Figure 5), charging time of capacitor (C) is considered as off-time or pulse interval, whereas discharging time is considered as pulse on-time. One important characteristics of RC power supply is that the breakdown or discharging voltage (V) is lower than the charging voltage, therefore, sometimes discharging starts before the capacitor is fully charged [28], which creates non-uniform discharge energy. The peak current is the amount of current that reaches before starting discharging. Considering $V=2V_g$ in equation 3, simplified form of the discharge energy per single pulse E_{RC} is expressed as,

$$E_{RC} = (1/2)\, CV^2 \qquad (4)$$

Where, C is the capacitance used for machining, V is the discharging voltage. Notably, the stray capacitor is simply added to the installed capacitor as the installed capacitor is parallel to the stray capacitor.

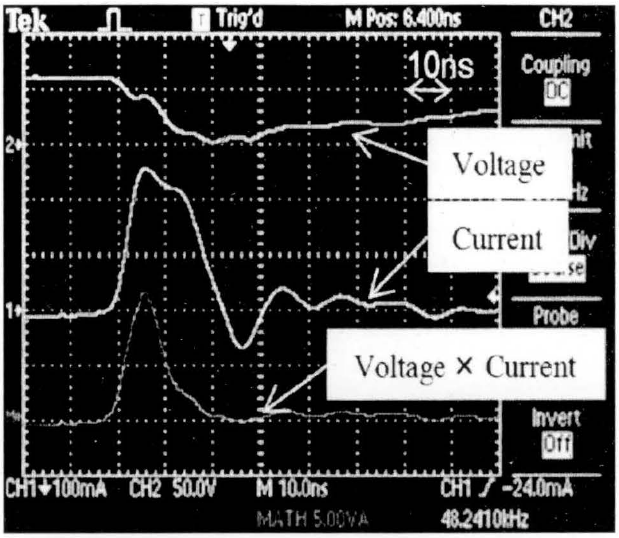

Fig 5. Current and Voltage Waveform from Discharge and Measurement of Discharge Energy in RC Power Supply [36]

3.2 Discharging, Breakdown, Open - Circuit and Gap Voltage

Discharge voltage in micro-EDM is related to the spark gap and breakdown strength of the dielectric.Breakdown voltage is the threshold voltage at which the initiation of breakdown occurs. However, before current can flow, the open gap voltage increases until it has created an ionization path through the dielectric. Once the current starts to flow, voltage drops and stabilizes at the working gap level. The voltage between the gap of the electrode and workpiece is known as gap voltage. The applied voltage determines the total energy of the spark. Higher voltage settings increase the gap, which improves the flushing conditions and helps to stabilize the machining and increase MRR. But at the same time, higher voltage will also contribute to poor surface roughness.

3.3 Peak Current

The term 'peak current' is often used to indicate the highest current during the machining. The higher the peak current, the larger is the discharge energy. During each on-time pulse, the current increases until it reaches a preset level, which is expressed as the peak current. Higher currents will improve MRR, but at the cost of surface finish and tool wear.

3.4 Pulse Duration

This is the duration of time the current is allowed to flow per cycle. The discharge energy is really controlled by the peak current and the length of the pulse on time. It is the 'work' part of the spark cycle, when the current flows and work is done only during this time. Material removal is directly proportional to the amount of energy applied during this time. With longer period of spark duration, the resulting craters will be broader and deeper; therefore, the surface finish will be rougher. Shorter spark duration on the other hand, helps to obtain fine surface finish. However, excessive pulse duration can be counter-productive [44].

3.5 Pulse Interval

This is the duration of time between two successive sparks when the discharge is turned off. Pulse off time is the duration of the rest or pause required for reionization of the dielectric. This time allows the molten material to solidify and to be washed out of the spark gap. If the pulse off time is too short, it will cause sparks to be unstable, and then more short-circuiting will occur. On the other hand, a higher pulse off time results in higher machining time, but it can provide stability required to successfully EDM a given application. When the pulse off time is insufficient as compared to ON time, it will cause erratic cycling and retraction of the advancing servo motors, slowing down the operation.

3.6 Duty Ratio or Duty Factor

Duty factor is a percentage of the pulse duration relative to the total cycle time. It is a measure of efficiency and is calculated by dividing the on time by the total cycle time. Generally, a higher duty factor means increased cutting efficiency. It is calculated in percentage by dividing pulse duration by the total cycle time (on-time + off-time).

3.7 Pulse Frequency

Pulse frequency is the number of cycles produced across the gap in one second. The higher the frequency, finer is the surface finish that can be obtained. With an increase of number of cycles per second, the length of the on-time decreases. Short on-times remove very little material and create smaller craters. This produces a smoother surface finish with less thermal damage to the workpiece. Pulse frequency is calculated by dividing 1000 by the total cycle time (on-time + off-time) in microseconds [44].

3.8 Electrode Polarity

Generally, during the micro-EDM process electrons are emitted from cathode and move towards the anode. After reaching the anode the electrons strike the anode surface to cause metal ion removed from the anode material. Therefore, it is the anode who losses more weight due to more material removal from its surface. This is the more common reason for getting high material removal rate when the workpiece is anode and electrode is used as cathode (negative polarity) [45].

3.9 Gap Control and Servo Feed

Unlike other micromachining processes, the electrode feed is not continuous during micro EDM The main purpose of the servo feed control is to maintain proper spark gap or gap width during the machining in addition to ensuring that the process is more stable by minimizing the open circuit, arcing and short-circuiting during machining. A stable gap control system enables better dimensional accuracy of micro machined features by predicting the gap distance and offsetting tool position [15].Larger gap width causes longer ignition delays, resulting in a higher average voltage. Tool feed speed increases when the measured average gap voltage is higher than the preset servo reference voltage and vice versa [26]. Other than the average gap voltage, the average delay time can also be used to monitor the gap width. In some cases, the average ignition delay time is used in place of the average gap voltage to monitor the gap width [46]. In addition, gap monitoring circuits can also identify the states and ratios of gap open, normal discharge, transient arcing, harmful arcing and short circuit [15].

3.10 Positioning Accuracy and Repeatability

During the micro-EDM, the accuracy and repeatability of positioning of the machine employed is a major source of errors [3]. For both the fabrication of micro-electrodes and fabrication of micro-features using on-machine fabricated micro-electrodes with high dimensional accuracy and repeatability, proper positioning accuracy should be maintained. The accuracy and repeatability of positioning of a micro EDM machine can be measured using a laser interferometer. To machine a micro-hole at a specific position, the accuracy of positioning of the machine will mainly affect the position of the hole, while the repeatability of positioning will impact on the size and shape of the hole. The accuracy of measurement is dependent on the speed of approach to the workpiece surface.The lower it is in relation to the speed of rotation ofthe electrode, the smaller the error will be.

3.11 Electrode Shape and Rotation

Electrode rotation can significantly enhance the flushing process in micro-EDM and significantly improve the overall performance of the micro-EDM as well as improve dimensional accuracy and surface finish. With the increase of electrode rotational speed the tangential velocities of the electrode increases which promote the disturbance of the dielectric [47]. The increased flow speed of the dielectric helps to depart the debris from the machined zone, thus facilitating further material removal from the workpiece. The relative electrode wears (RWR) decreases with the increase of electrode rotational speed. The electrode shape can certainly improve the flushing condition and overall performance of the micro-EDM. Improved flushing of debris has been reported by using a single-side notch electrode compared to cylindrical electrode [47]. Using a helical micro-tool electrode for micro-EDM combined with ultrasonic vibration can substantially reduce the EDM gap, taper and machining time for deep micro-hole drilling [48].

3.12 Wire Tension and Wire Speed in W-EDM

The amount of wire tension affects the dynamic stability condition of the micro-WEDM process. The deflection of the wire happens due to different kind of forces working on it, such as electromagnetic force, flushing pressure and pressure of the spark. If tension is less, there is a greater chance of wire bending and also inaccuracy in machining. Because of continuous motion of the wire, if proper tension is not maintained, there could be high vibration at the machining area. This can cause to undesirable gap width, excessive short circuit and even wire breakage. Too high wire tension again can cause the wire to break often. Wire speed is the relative velocity of the wire at which it moves across the workpiece during machining. The speed of the wire should not be too high so as to reduce the usage of the wire. At very slow speeds the wire tends to break more often, since the same region gets eroded more, reducing the tensile strength of the wire.

3.13 Wire Tension and Wire Speed in W-EDM

During micro-EDM, to maintain stable machining, it is critical to flush debris particles and cool the working gap in order to prevent the localization and concentration of discharge locations [26]. High flushing pressure can improve the overall flushing mechanism; improve machining stability and MRR during micro-EDM, especially in micro EDM drilling. However, very high pressure can increase position error in addition to reducing dimensional accuracy due to deflection of the thin electrode used in micro-EDM. On the other hand, the particles generated in micro-EDM can quickly accumulate due to the lack of flushing pressure and create a electrical short condition between the electrodes. This is aggravated by the fact that in moderate settings of micro-EDM voltage, the spark gap can be as small as 3 ~ 4 µm. Pressure or suction flushing through holes in the electrode or workpiece remains one of the most efficient flushing methods at least if those holes have to be provided anyway or does not harm the workpiece.

A special rotary electrode movement to enhance the pumping action of dielectric fluid during the lifting motion has been applied [49]. Orbiting of the tool or workpiece has also been found to assist flushing and improve machining conditions. In addition, the flushing direction can have significant influence on the machining performance. Flushing from one direction can cause increased density of debris particles in the downstream, resulting in uneven distribution of gap width deteriorating the machining accuracy [50]. Therefore, sometimes flushing from both sides, alternate flushing and sweeping flushing is preferable.

3.14 Tolerance and Limitation of Miniaturization in Micro-EDM

As micro-EDM has much promise for the fabrication of micro-features, it is important to understand the various factors affecting the minimal dimensions achievable by micro-EDM. The minimum feature size attainable by a micro-EDM setup is not merely limited by the precision of the motion devices and electrodes used, but mainly coupled to the spark energy delivered in every quantum and can be estimated by simple knowledge of the roughness of a surface created by every crater at the applied energy being employed. It is postulated that a feature size is defined as unachievable when there is no material left in some places of a machined feature due to overlapping of valleys from one surface to the valleys of the adjacent surface. Therefore, minimum attainable feature size can be estimated from the accuracy of the motion control system and a delta amount added to the 2 times of R_z - average distance between the highest peak and lowest valley formed from the spark energy provided by the power supply settings. This has been illustrated in Figure 6 [51], taking the case of machining a vertical wall as a feature and therefore, milling micro-EDM is performed on both sides of the wall. In the schematic, top view of wall is shown which experienced micro-EDM on both sides of the wall. When the two rough surfaces overlap, as in the second case, the machined structure becomes discontinuous due to overlapping of valleys causing formation of holes in the wall resulting in unsuccessful machining of the feature.

In addition, the limitation and tolerances of miniaturization in micro-EDM depends greatly on residual stress, subsurface layer damages, and material structure of workpiece [26]. It was found that cemented tungsten carbide micro rods (grain size 0.4 μm) smaller than 2.3 μm in diameter could not be obtained by micro EDM even after a large number of repeated experiments [52–54]. The minimum diameter of the micro rod was found to be almost the same whether the rod is used as anode or cathode in WEDG.By reducing the open circuit voltage to 20 V, a minimum rod diameter of 1 μm was obtained [15]. The minimum machinable thickness of a micro wall was thinner when mono crystal tungsten was used compared with poly crystal tungsten. However, since cracks were generated parallel to it, it is not always true that the mono-crystal is more suitable for miniaturization than poly-crystal.

4. NOVEL PROCESSES AND APPLICATIONS

An exhaustive description on micro-EDM processes and applications have been presented by Jahan et al., [55]. In this article, only a few

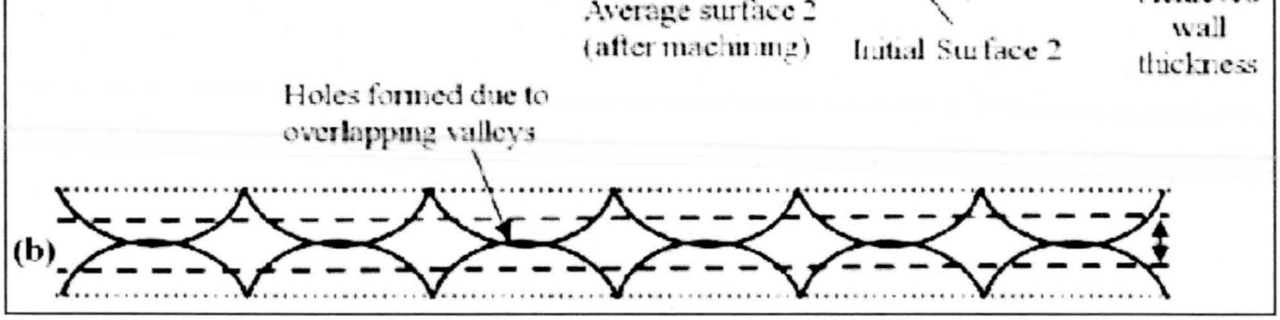

Fig 6. Schematic Showing the Simplified Estimation of Minimum Achievable Feature Size from Crater Size of Micro-EDM [51]

innovative applications are presented in the following sections.

4.1 On-Machine Electrode Machining

The non-contact nature of micro-EDM makes it possible to use a very long and thin electrode for machining tough die material. However, during micro-EDM it is not recommended to change the microelectrode during machining, because it incurs inaccuracy due to the change in setup or re-clamping of the micro-electrode. From an electrode bigger than the required diameter, a cylindrical electrode is fabricated by EDG process using a sacrificial electrode. Different setup and trajectory control of the sacrificial electrode can be used in this process, such as using a 'stationary block', 'rotating disk', 'wire EDG (WEDG)' and moving BEDG etc. Figure 7 shows the fabricated micro electrodes using stationary BEDG, moving BEDG and micro-WEDG and rotating disk EDG process. Figure 7(a) shows a 44.5 µm CuW electrode by stationary BEDG. Figure 7(b) shows an example of 45 µm W electrode by moving BEDG process [38]. Figure 7 (c) and (d) are examples of 10 µm electrode fabricated by micro-WEDG process [56] and 4.3 µm diameter shaft by micro-WEDG process [54], respectively.It has been reported that, among the various micro-EDM techniques for on-machine fabrication, micro-WEDG and moving BEDG can produce dimensionally more accurate micro electrodes with better surface finish. However, micro-electrodes with lowest diameter of 4.3 µm diameter were obtained by micro-WEDG process.

4.2 On-machine PCD Cutting Tool Machining

Micro-tools made of PCD offer new promise for micromachining hard and brittle materials. PCD consists of micrometer-sized diamond grains sintered under high temperature and pressure with metallic cobalt [57]. The cobalt fills the interstices between the diamond particles and forms an electrically conductive network. This conductivity makes PCD suitable for micro-EDM process and this provides an opportunity to fabricate micro-size micro-grinding tool. After shaping, the surface of a PCD tool contains protruding diamond grains that are randomly distributed, which can act as hard and tough cutting edges for micro-grinding. The feasibility of micromachining glass and ceramic materials with PCD micro-tools that are prepared in a variety of shapes using the non-contact micro-EDM process has been proposed by Morgan et el. [57]. The PCD tool contains randomly distributed protrusions of diamond with dimensions in the range of few microns that serve as the cutting edges for micromachining on glass. They found that in cases where the depth of cut was too large, brittle fractures around the edges of the grooves or pockets were observed and where the depth of cut was below brittle-to-ductile transition, brittle fractures were not apparent and ductile cutting marks were clearly evident on the machined surfaces, and PCD tools showed very little wear.

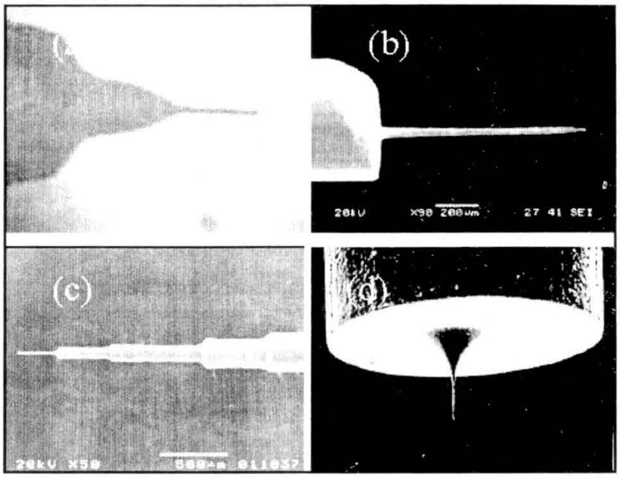

Fig 7. Examples of On-Machine Fabricated Micro-Electrodes by Micro-EDM Process

Masaki, T., et al. [58], presented further results in using PCD to accomplish the micro-shape grinding of micro-freeform surfaces. They fabricated a spherical PCD tool by EDG with a pin gauge tool electrode made of tungsten carbide that was manufactured precisely by controlling its diameter and straightness. Using this spherical PCD tool fabricated on-machine they performed a series of micromachining of various shapes from flat, concave, convex to freeform machining and achieved mirror surface finish on tungsten carbide with surface roughness of 5nm Ra. On conventional machining center ball endmills are used for milling of a variety of complex shapes. A ball endmill has a normal hemisphere and therefore four or five axis control is necessary to realize the high degree of freeform shaping and convex and concave shapes machining. They demonstrated that the micro EDMed spherical PCD tool, which has innumerable cutting edges uniformly located along its entire surface, can be used for machining orthogonal micro-freeform shapes on XY and YZ plane using a 3 axis machining platform (Figure 8(a)). Figure 8(b) shows the concept of freeform machining from one direction can cause increased density of debris particles in the downstream, resulting in uneven distribution of gap width deteriorating the machining accuracy [50]. Therefore, sometimes flushing from both sides, alternate flushing and sweeping flushing is preferable.

3.14 Tolerance and Limitation of Miniaturization in Micro-EDM

As micro-EDM has much promise for the fabrication of micro-features, it is important to understand the various factors affecting the minimal dimensions achievable by micro-EDM. The minimum feature size attainable by a micro-EDM setup is not merely limited by the precision of the motion devices and electrodes used, but mainly coupled to the spark energy delivered in every quantum and can be estimated by simple knowledge of the roughness of a surface created by every crater at the applied energy being employed. It is postulated that a feature size is defined as unachievable when there is no material left in some places of a machined feature due to overlapping of valleys from one surface to the valleys of the adjacent surface. Therefore, minimum attainable feature size can be estimated from the accuracy of the motion control system and a delta amount added to the 2 times of R_z - average distance between the highest peak and lowest valley formed from the spark energy provided by the power supply settings. This has been illustrated in Figure 6 [51], taking the case of machining a vertical wall as a feature and therefore, milling micro-EDM is performed on both sides of the wall. In the schematic, top view of wall is shown which experienced micro-EDM on both sides of the wall. When the two rough surfaces overlap, as in the second case, the machined structure becomes discontinuous due to overlapping of valleys causing formation of holes in the wall resulting in unsuccessful machining of the feature.

In addition, the limitation and tolerances of miniaturization in micro-EDM depends greatly on residual stress, subsurface layer damages, and material structure of workpiece [26]. It was found that cemented tungsten carbide micro rods (grain size 0.4 µm) smaller than 2.3 µm in diameter could not be obtained by micro EDM even after a large number of repeated experiments [52–54]. The minimum diameter of the micro rod was found to be almost the same whether the rod is used as anode or cathode in WEDG.By reducing the open circuit voltage to 20 V, a minimum rod diameter of 1 µm was obtained [15]. The minimum machinable thickness of a micro wall was thinner when mono crystal tungsten was used compared with poly crystal tungsten. However, since cracks were generated parallel to it, it is not always true that the mono-crystal is more suitable for miniaturization than poly-crystal.

4. NOVEL PROCESSES AND APPLICATIONS

An exhaustive description on micro-EDM processes and applications have been presented by Jahan et al., [55]. In this article, only a few

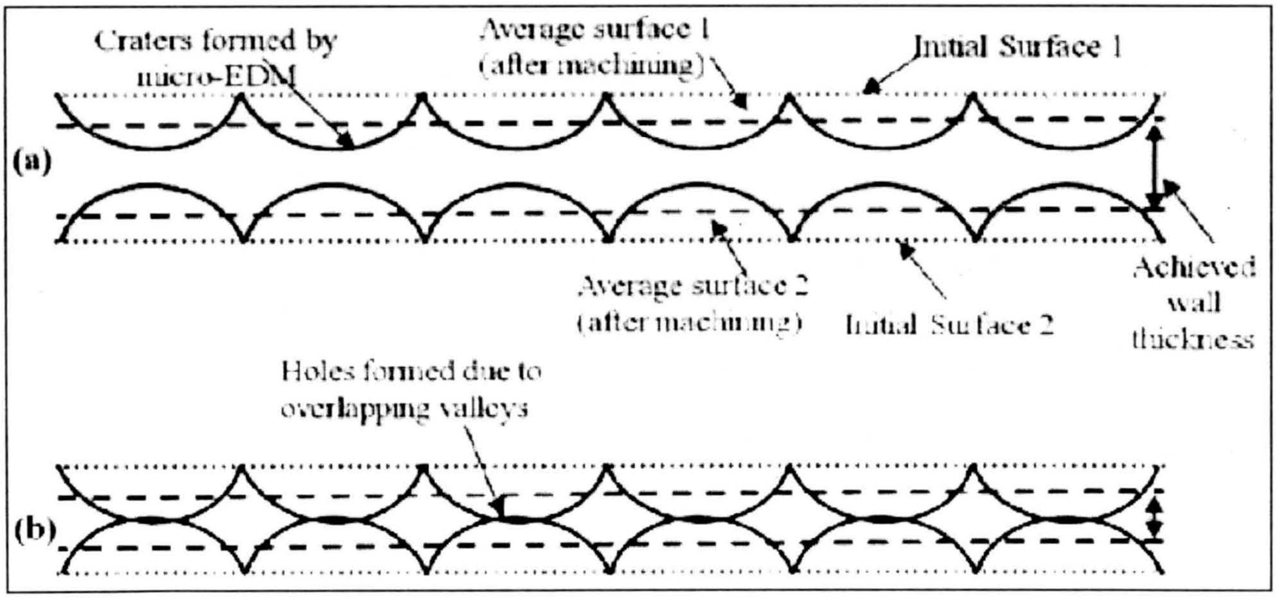

Fig 6. Schematic Showing the Simplified Estimation of Minimum Achievable Feature Size from Crater Size of Micro-EDM [51]

innovative applications are presented in the following sections.

4.1 On-Machine Electrode Machining

The non-contact nature of micro-EDM makes it possible to use a very long and thin electrode for machining tough die material. However, during micro-EDM it is not recommended to change the microelectrode during machining, because it incurs inaccuracy due to the change in setup or re-clamping of the micro-electrode. From an electrode bigger than the required diameter, a cylindrical electrode is fabricated by EDG process using a sacrificial electrode. Different setup and trajectory control of the sacrificial electrode can be used in this process, such as using a 'stationary block', 'rotating disk', 'wire EDG (WEDG)' and moving BEDG etc. Figure 7 shows the fabricated micro electrodes using stationary BEDG, moving BEDG and micro-WEDG and rotating disk EDG process. Figure 7(a) shows a 44.5 µm CuW electrode by stationary BEDG. Figure 7(b) shows an example of 45 µm W electrode by moving BEDG process [38]. Figure 7 (c) and (d) are examples of 10 µm electrode fabricated by micro-WEDG process [56] and 4.3 µm diameter shaft by micro-WEDG process [54], respectively.It has been reported that, among the various micro-EDM techniques for on-machine fabrication, micro-WEDG and moving BEDG can produce dimensionally more accurate micro electrodes with better surface finish. However, micro-electrodes with lowest diameter of 4.3 µm diameter were obtained by micro-WEDG process.

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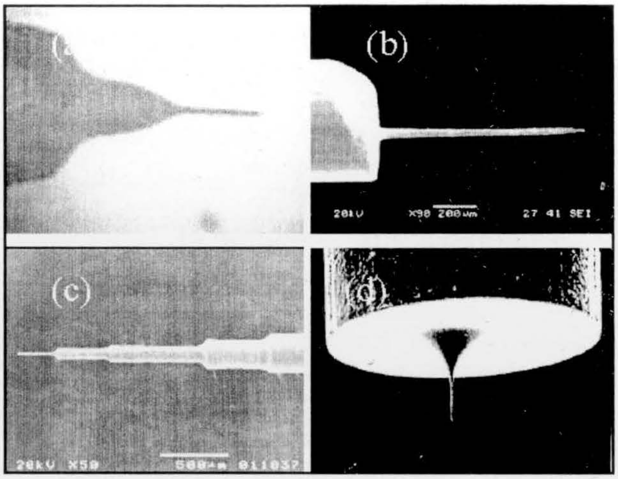

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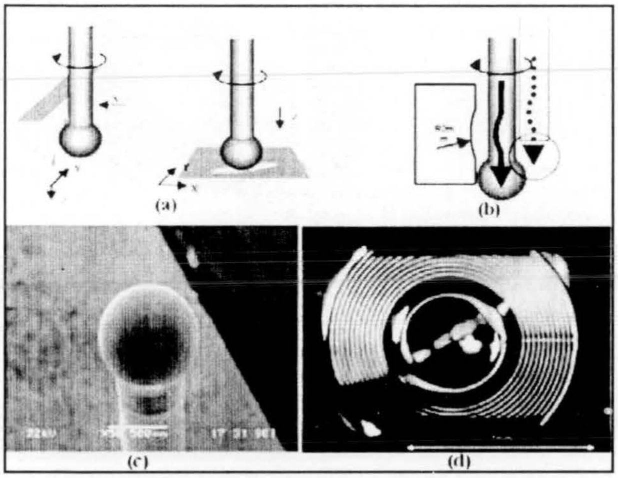


Fig 8. Example of Freeform Micromachining Using on-machine Fabricated PCD Ballend Tool

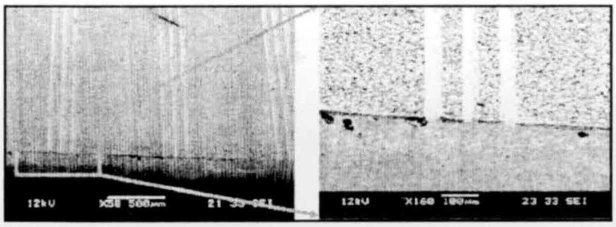


Fig 9. 15μm Deep and 35μm wide Slots Machined by Micro-Milling Using PCD Micro Tool on PZT Substrate Coated with Ag.

using the on-machine fabricated spherical PCD tool shown in Figure 8(c) and image of a shaped convex spherical surface on tungsten carbide is shown in Figure 8(d). Figure 9 shows another example of a 35μm wide slot machined by micro-milling using PCD micro tool on PZT substrate [59].

4.3 Ultra-sharp Microturning Tool Fabrication

Commercially available PCD inserts, designed for light finishing cut, has a relatively large tool nose radius e.g., 100μm [Figure 10(a)]. This tool nose resolves the cutting force on the shaft into two components, namely F_x and F_y, as can be seen in Figure 10(a). The F_y component of the cutting force does the actual cutting while the F_x component causes deflection of the micro shaft. A commercially available PCD insert can be modified to achieve a very sharp cutting edge, so as to reduce the F_x component of the cutting force significantly which is illustrated in Figure 10(b). Thus this makes it possible to achieve a straight shaft of a much smaller diameter. A comparison of the micro-shafts fabricated with round tool nose and modified tool nose is shown in Figure 10(c) and 10(d), respectively.

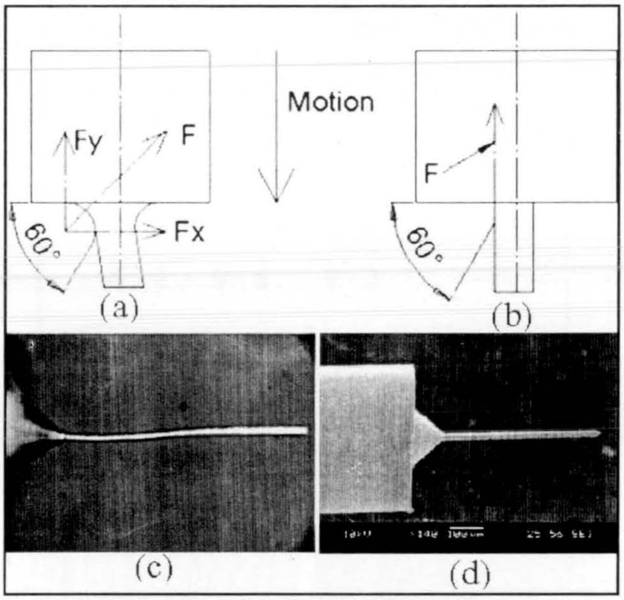


Fig 10. Example of Microturning Using on-Machine Modified PCD Turning Insert [38].

4.4 Repetitive Pattern Transfer and Batch Processing

In recent years, micro-EDM has been found to be a flexible technique for repetitive pattern transfer batch processing. The microstructures that are found to be frequently patterned using micro-EDM are the arrays of micro-holes, micro-disk, or micro-slit. The major advantage of micro-EDM as a pattern transfer and batch mode processing technique over LIGA and other photographic technique is that, it can be applied to a wide range of materials. Miniature parts with high-density micro holes are often used in the micro mask in the MEMS process, biochips for handling individual embryo cells, ultrasonic vibration assisted atomizer for the treatment of medicine and the micro device in aerostatic air bearing systems [60]. A large number of micro holes are needed for biomedical parts, ink-jet nozzles and micro droplet spraying parts.

There are several micro-EDM based techniques that have been applied successfully for the batch mode production. Figure 11(a) shows a novel approach to improve the throughput in micro EDM [61,62]. In the first step (n=1), a single micro cylindrical electrode is made by WEDG. In the second step (n=2), a plate electrode is perforated to have a pattern of holes using the cylindrical electrode made in the first step. In the third step (n=3), using the plate electrode as tool electrode, the pattern is replicated to a block workpiece. In the next step (n=4), the workpiece is

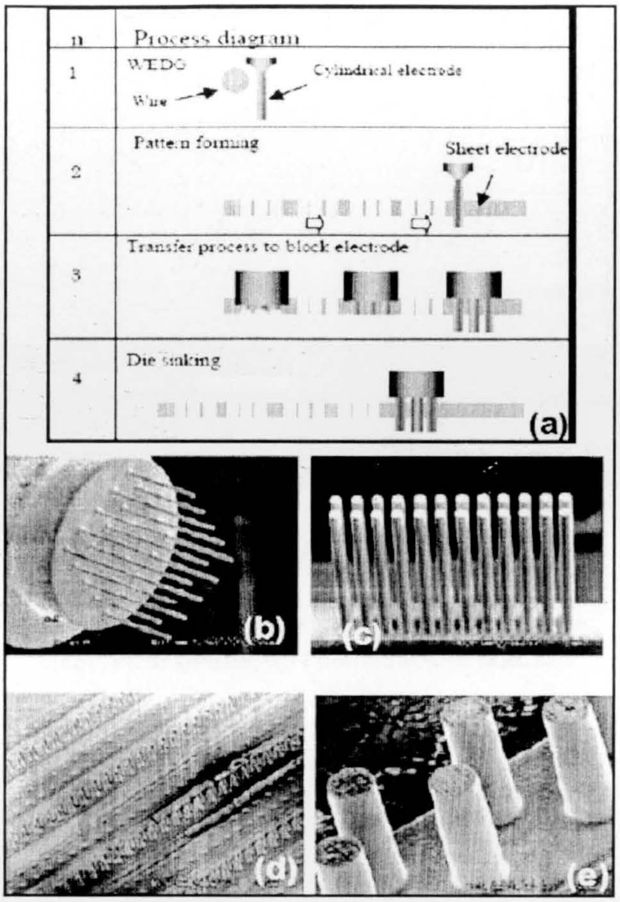


Fig 11. Example of Repetitive Pattern Transfer Process [61,62]

used as tool electrode to make many patterns of holes precisely and efficiently. After this, steps of 3 and 4 may be repeated to obtain numerous numbers of holes. Cu-W multi electrode of 14.3μm dia, a WC micro pin mold and a STAVAX micro taper pin mold shown in Figure 11(b) to (d).

4.5 3D Micro-Mold Machining by Micro-EDM Milling

Micro-molds with widely spread microstructures, such as those needed in glass embossing processes for flat panel displays, can often not be structured by micro-WEDM or die-sinking micro-EDM due to their dimensions. Micro-EDM milling is mainly used when large and complex geometries are required. As an alternative, micro-EDM milling can be used in which a path-controlled multi-axis feed motion is performed between rotating tool electrode and work piece. The use of geometrically simple rotating electrodes significantly decreases effort and costs for electrode production. Either commercially available micro-electrodes can be used or micro-electrodes can be machined on-machine by micro-EDG process. The minimum structure dimensions are determined by the diameter of the pin electrodes and the gap width. Figure 12 shows the various micro-cavities fabricated by using milling micro-EDM with on-machine fabricated electrode. Figure 12(a) shows micro cavity in hot forming tool steel using simple electrode of 100 μm [63] whereas Figure 12(b) is the 1/8 Ball in a square cavity [64]. Figure 12(c) is the small pyramid (L: 25 mm, W: 25 mm, H: 35 mm, step size 7 mm) by micro - EDM milling [38] and Figure 12(d) shows two 10 μm slots with 2.5 μm thick separating wall on a 50μm thick SUS 304 stainless steel [38].

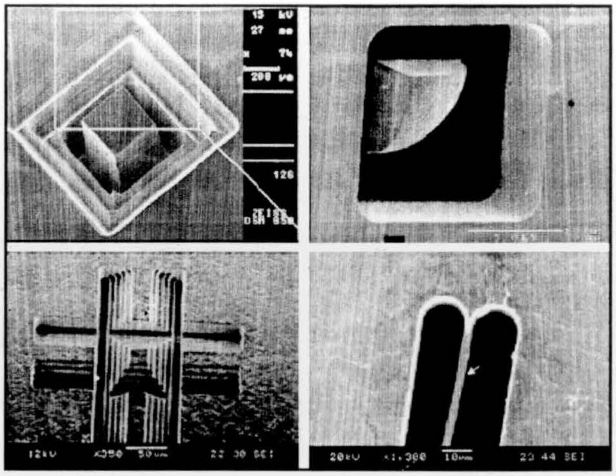
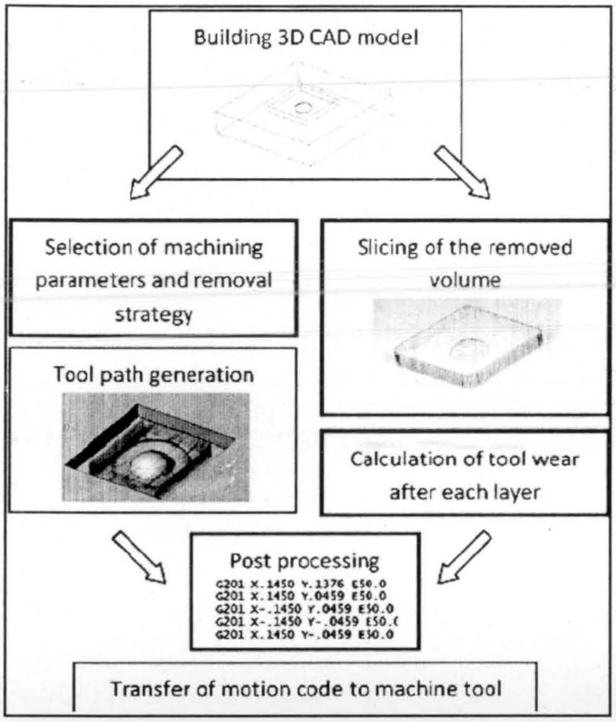


Fig 12. Example of 3D Micro-Mold Machining by Micro-EDM Milling

In order to machine intricate features by micro-EDM milling process, it requires the application of computer-aided manufacturing (CAM) software to automatically generate the motion pattern for the electrode. Although most commercial CAM systems cater for conventional milling, they cannot be directly applied for micro-EDM milling due to the electrode wear issue and the existence of machining gap during machining. Hence, an attempt has been carried out to customize the conventional milling CAM software for micro-EDM milling of 3D intricate shapes.

In the commercial CAM systems which mainly caters for conventional milling, the tool shape and tool length are presumed to be unchanged during the entire machining process. Hence, it is required to be modified and developed for 3D micro-EDM milling. Figure 13 shows the tool path generation system used in this study which has been developed based on the Solid Works and the ESPRIT CAM environment. In this system, the compensation of machining gap is performed



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G201 X.1450 Y.1376 E50.0
G201 X.1450 Y.0459 E50.0
G201 X-.1450 Y.0459 E50.0
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G201 X.1450 Y-.0459 E50.0
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Fig 13. Tool Path Generation System

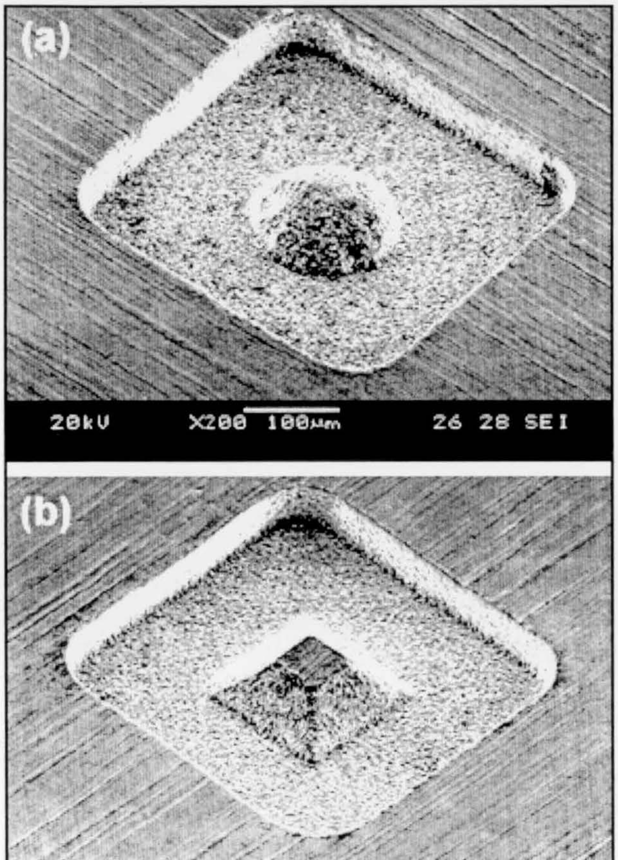

Fig 14. SEM Images of Fabricated Micro-Shapes: (a) Micro-Dome and (b) Micro-Pyramid

in the second step whereas the electrode wear compensation is realized at step 4, 5 and 6. The details of each step are given as below.

Figure 14 shows the scanning electron micrographs of the obtained micro-shapes. This indicates that the developed tool path generation is capable of realizing the machining code for 3D micro-EDM milling. In order to analyze the profile accuracy, Figure 15(a) compares the measured cross-sectional profiles of the fabricated shapes with their ideal profiles. It could be seen that the side and the bottom sections of micro cavities have the relatively good fit with the ideal profile owing to electrode wear and machining gap compensation. However, it is realized that the curved section of micro-dome are apart from the ideal profile by a small distance.

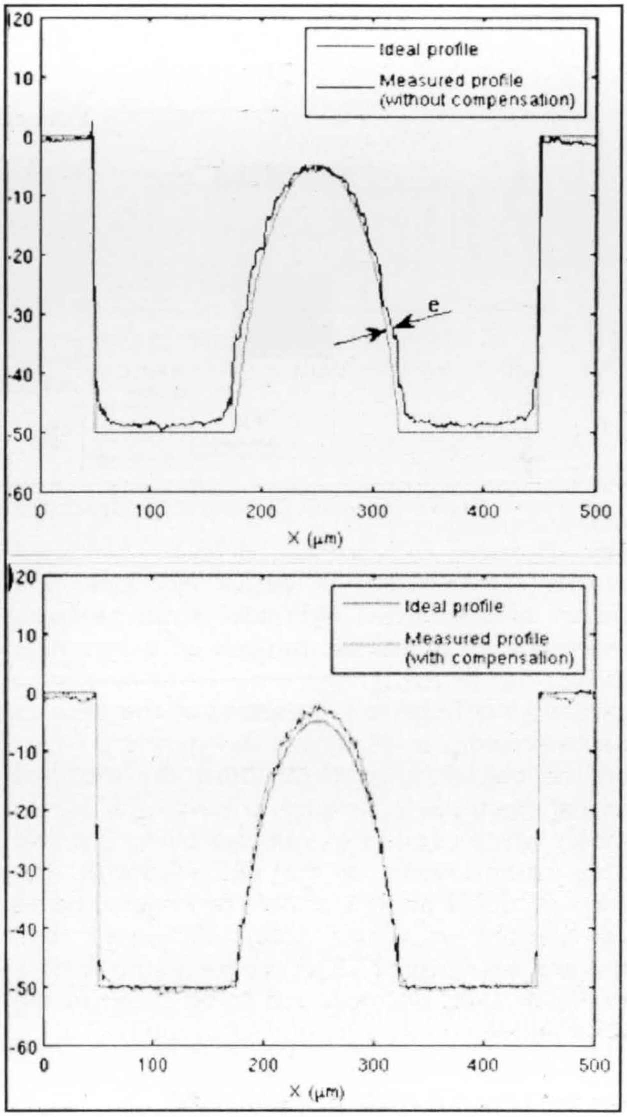

Fig 15. Measured Profiles Vs. Ideal Profiles of Fabricated Micro-Shapes With Corner Radius Compensation

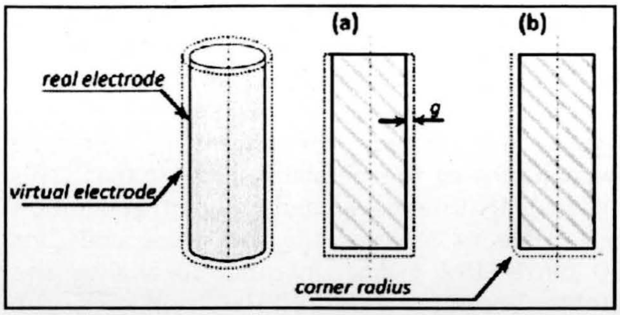

Fig 16. Illustration of Virtual Electrode Geometry: (a) Without Corner Radius and (b) With Corner Radius

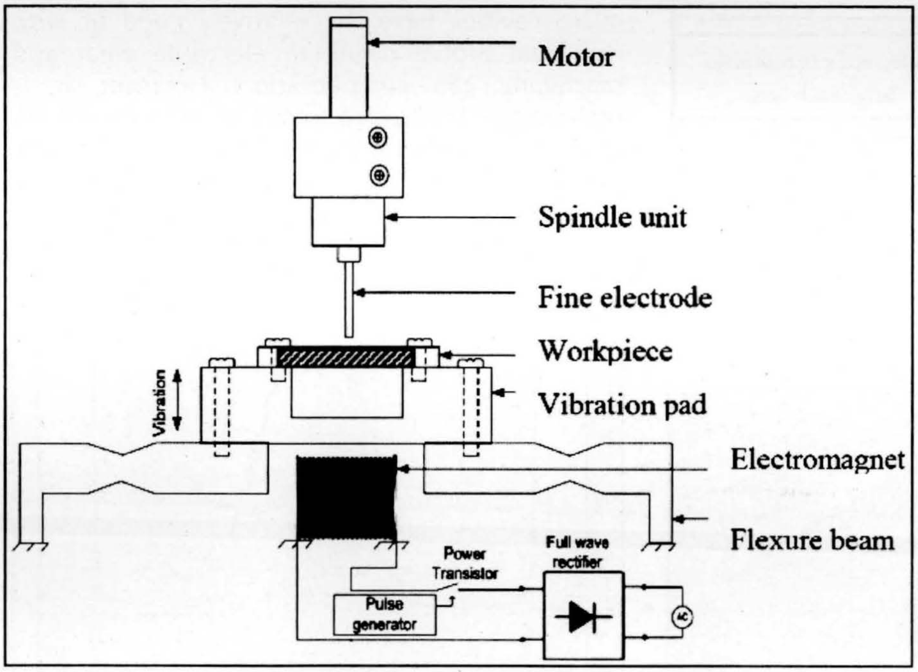

Fig 17. Schematic Diagram of the Developed Vibration Unit

This deviation is hypothesized to be attributed to the corner radius of virtual electrode. The corner of the virtual electrode is not perfectly sharp and it should be rounded off with a fillet radius due to the limited distance of machining gap and the imperfect sharpness at the edge of real electrode, as illustrated in Figure 16. Based on the machining condition used, the modified virtual electrode is defined to have 6μm corner radius which consists of 5μm machining gap and 1μm corner radius of the real electrode. The cross-sectional profiles of obtained micro shapes are plotted in Figure 15(b). Compared with the profiles in Figure 15(a), the measured profiles in Figure 15(b) are observed to be closer to the ideal profiles.

4.6 Vibration Assisted Micro-EDM

The machining of deep micro-holes is a challenge in manufacturing. Presently, micro-EDM has been found to be an effective method of drilling micro-holes in conductive materials, irrespective of hardness, strength and wear resistance. However, the application of micro-EDM in deep-hole drilling is still limited due to the difficulty in flushing of debris and unstable machining. Hence, low-frequency workpiece vibration device for deep-hole micro EDM drilling is a good resolution to overcome the aforementioned problems [38].

In order to create a low frequency oscillation on the work-piece a simple vibration device has been designed and developed. The schematic of the whole system is shown in the Figure 17. An electromagnet is used as the actuator. The electric power is supplied periodically to the electromagnet with the help of a power transistor switch. The ON-OFF sequence of the power transistor is controlled by a frequency controllable pulse generator. When the switch is kept ON the electricity flowing through the circuit causes the electromagnet to be energized which triggers a pull action on the vibration pad. The flexure beams are bent at that time. The electromagnet is de-energized when the transistor switch is turned OFF, which causes the flexure beams to release and pushes the vibration pad in upward direction. This is how a low frequency oscillation is induced on the work-piece material. Figure 18 shows the surface topography showing crater sizes at the inner surface of the micro holes obtained at 100 V, 10 nF for without and with vibration at f = 750 Hz, a = 1.5 μm. It has been observed that,the craters are of comparatively broader sizes on the surface obtained without vibration. In addition, there is a resolidified crater attached on the surface which deteriorates the surface finish. The broader crater sizes are the cause of more micro-hole expansion when machining without vibration. On the other hand, the surface obtained using vibration assisted micro-EDM is smoother and composed of comparatively small size craters at the same electrical settings.

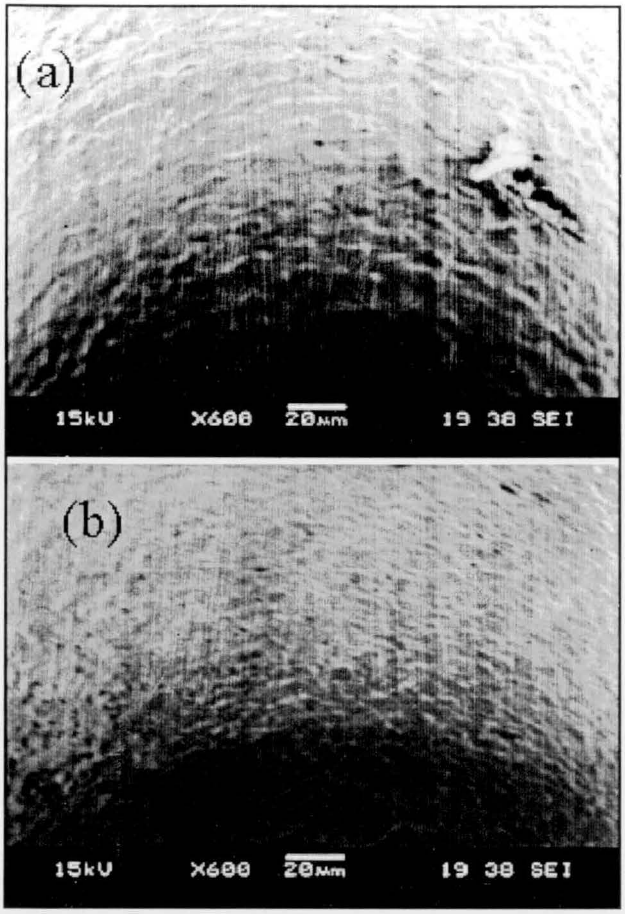

Fig 18. Comparison of Crater Sizes and Surface Topography for Micro-EDM (a) Without Vibration and (b) With Vibration

4.7 Nano Powder Mixed Micro-EDM

Powder mixed electric discharge machining (PMEDM) is one of the recent innovations for the enhancement of capabilities of EDM process [65]. In PMEDM, the electrically conductive powder is mixed with the dielectric of EDM. Hence, it reduces the insulating strength of the dielectric fluid and increases the spark gap between the electrode and workpiece [66,67]. As a result, the process becomes more stable and thus the material removal rate (MRR) and surface finish are improved [65,68]. Figure 19 shows the principle of powder mixed EDM.

During machining, the spark gap between the electrode and workpiece is filled up with powder particles. When a voltage is applied between the electrode and the workpiece, the powder particles become energized and behave in a zigzag fashion. These charged particles are accelerated by the electric field and act as conductors. The conductive particles promote the early breakdown in the gap and increase the spark gap between the electrode and the workpiece. Due to bridging effect, the insulating strength of the dielectric fluid decreases. The early breakdown of dielectric occurs, causing early explosion in the gap. The faster sparking causes faster erosion from the workpiece surface and hence the material removal rate increases. At the same time, the added powder also modifies the plasma channel. The pulse discharge energy is

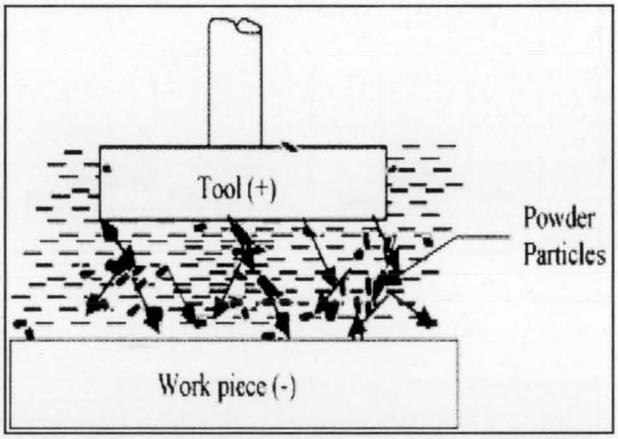

Fig 19. Principle of Powder Mixed Micro-EDM [69]

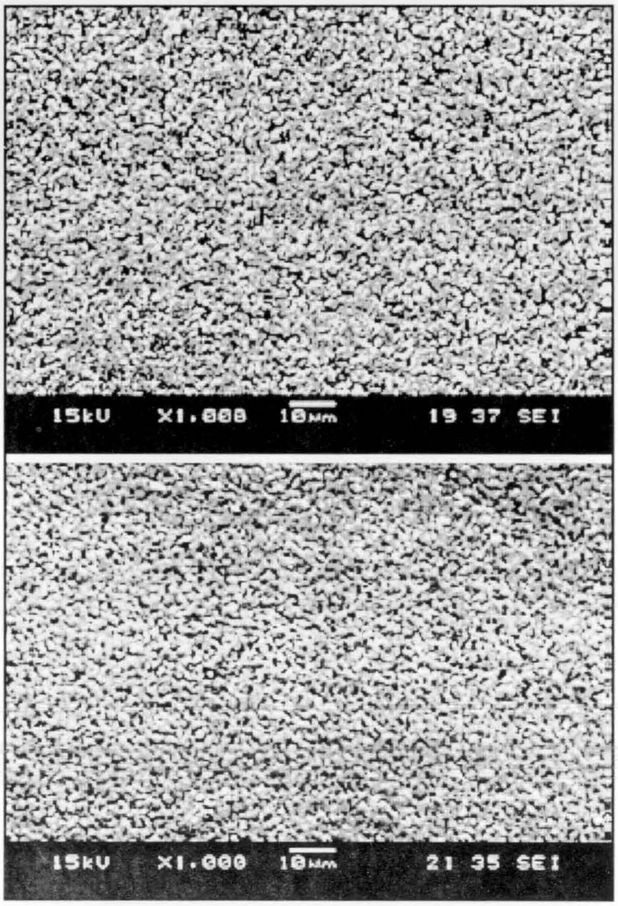

Fig 20. Machined Surface Topography in Milling Micro-EDM (a) Without Powder and (b) With Graphite Powder Mixed Dielectric

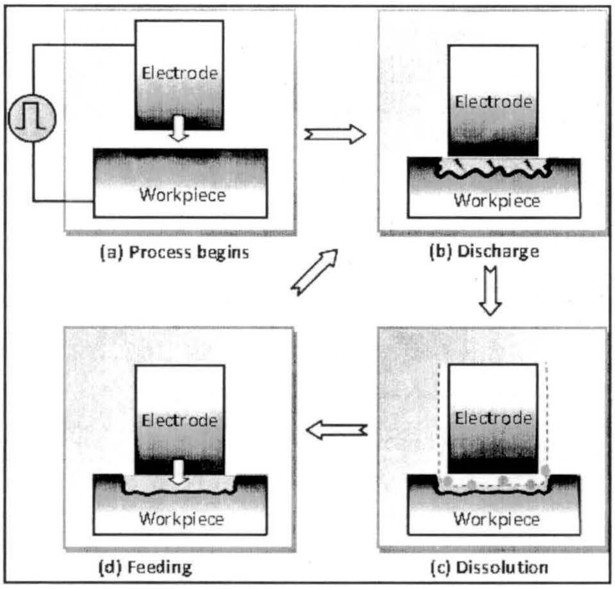

Fig 21. Principle of SEDCM Process

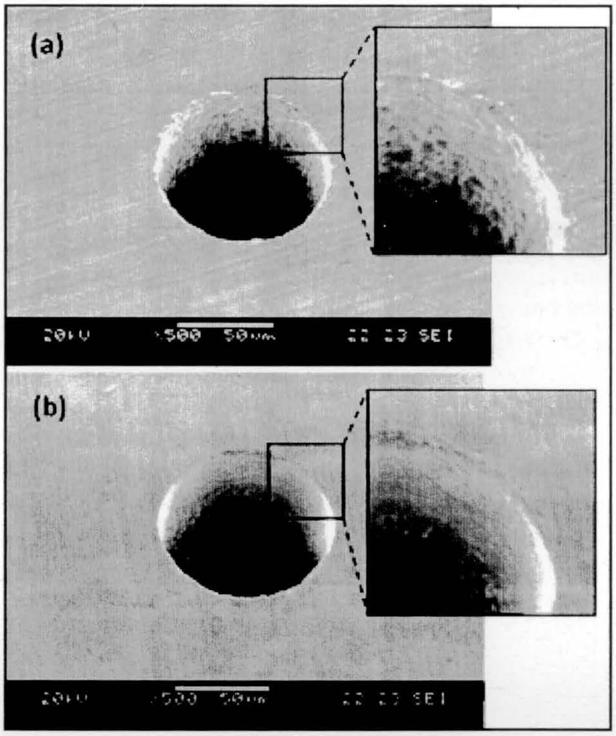

Fig 22. Micro-Holes Fabricated by Conventional Micro-EDM (a) and SEDCM (b)

uniformly dispersed among the powder particles. Hence, the pulse energy of each spark decreases. As a result, shallow craters are formed on the workpiece surface resulting in improvement in surface finish. In addition, sometimes there may be some abrasive action of the powder particles, which can improve the surface finish by reducing the deposited debris and also the crater boundary heights.

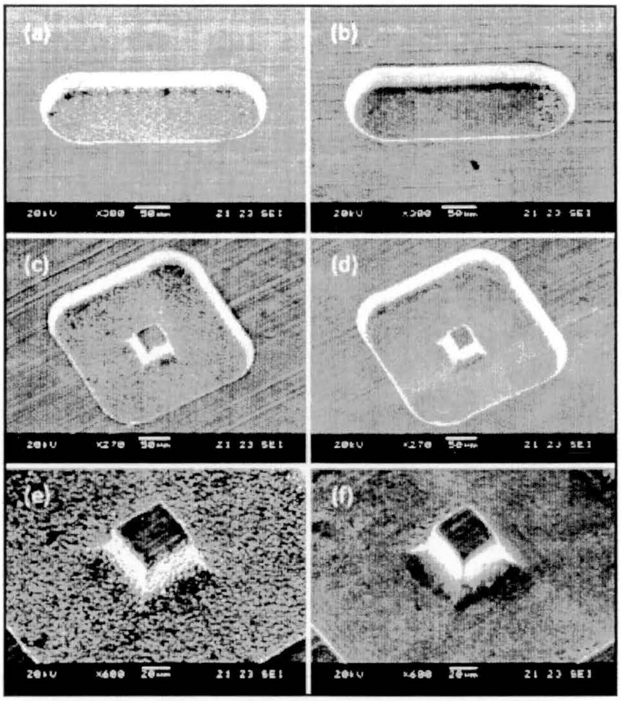

Fig 23. Different Micro-Shapes Fabricated by Conventional Micro-EDM (a, c, e) and SEDCM (b, d, f)

Figure 20 presents the comparison of machined surface topography for die-sinking and milling micro-EDM for without and with the addition of graphite nano-powders in dielectric oil. The machined surface topography has been improved after the addition of graphite nanopowders. An average reduction of 20-30% in R_a was obtained after using powder mixed micro-EDM. The lowest value of R_a (38 nm) was obtained in powder mixed milling micro-EDM, which was found to be about 49 nm without powder.

Figure 21 shows the principle of SEDCM in low-resistivity deionized water. In this process, short voltage pulses are applied instead of a continuous voltage in the normal micro-EDM using RC-type pulse generator. When the process begins, short voltage pulses are applied across the electrode and workpiece. Then, the electrode is lowered down to reduce the gap between electrode and workpiece, as shown in Figure 21(a). When the gap meets a critical value, there is the breakdown of deionized water and the sparks occur as shown in Figure 21(b). Material is removed from the workpiece by melting and vaporization. Each discharge leaves a crater on the machined surface. Therefore, the surface is covered with a multitude of overlapped discharge craters and it is rather rough, as a result. After a period of time, the gap width between electrode and workpiece increases due to material eroded by the sparks and no further discharges

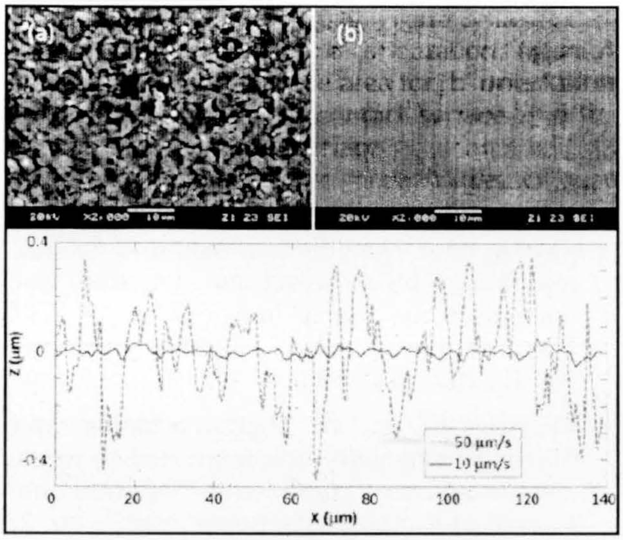

Fig 24. Topography of Surfaces Generated by Conventional Micro-EDM (a) and SEDCM (b)

occur. With the continuous supply of voltage pulses, the electrochemical reaction occurs owing to the slight conductivity of deionized water, as illustrated in Figure 21(c). Material is dissolved from the workpiece and its surface roughness decreases. Due to the usage of short voltage pulses, the dissolution of material is localized within a certain distance which is marked with dotted line in Figure 21(c) [71]. Hence, the machining gap is confined and the machining accuracy could be constrained. After a second, the electrode is lowered down further through feeding and the process repeats the cycle as illustrated in Figure 21 (d). In order for the electrochemical reaction to have enough time to dissolve material, the feedrate must be sufficiently low. In short, there are three main factors in SEDCM: low-resistivity deionized water as bi-characteristic fluid, moderate feedrate to promote the electrochemical reaction and short voltage pulses to localize the dissolution zone.

Figure 22(a) shows the micro-hole fabricated by conventional micro-EDM whereas Figure 22(b) exhibits the hole machined by SEDCM using 500 kHz pulses with 30% duty cycle. In Figure 22(a), the micro-hole surface is observed to be covered by overlapped discharge craters; especially, the recast material can be visibly seen at its rim. On the contrary, the lateral surface of micro-hole machined by SEDCM is found to be smooth and free of crater (Figure 22(b)). This shows that SEDCM could yield better surface finish because the uneven material layer generated by micro-EDM is dissolved by the electrochemical reaction. As a result, the diameter of hole generated by SEDCM is slightly larger than that of hole generated by conventional micro-EDM. This is in accordance with the experimental results: the machining gap of SEDCM is around 8μm while it is less than 6μm for conventional micro-EDM.

Figure 23 shows the SEM micrographs of micro-slots and cavities machined using conventional micro-EDM and SEDCM. It can be seen that the surface of machined shapes is entirely covered with discharge craters in micro-EDM. In SEDCM, the obtained surface is found to be rather smooth. Figure 24 exhibits the topography of these generated surfaces. Overlapping craters having diameter of 3~4 microns could be seen in Figure 24(a) whereas a relatively smooth surface with no visible crater is obtained in Figure 24(b). For quantitative comparison of surface finish, the average surface roughness (R_a) of micro-EDMed surface is 142nm while it is found to be 22nm only for SEDCM. This substantiates that SEDCM could yield better surface finish compared to micro-EDM alone owing to the effect of electrochemical reaction.

5. CONCLUSIONS

The capability of machining intricate micro-features with high dimensional accuracy in hard and difficult-to-cut materials has made micro-EDM as an inevitable and one of the most popular micromachining processes. In recent years, micro-EDM has found important industrial applications, such as in the fabrication of automotive nozzles, spinnerets, micro-moulds and dies, fiber-optics and MEMS, aerospace, medical and biomedical applications, micro-electronics & micro-tools.

This article presented an overview on micro-EDM process, including the physical principle of micro-EDM, power supply, different process control parameters such as electrical, non-electrical, and mechanical and motion control parameters, and novel micro-EDM processes and applications.

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