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1.10 Micro-EDM Drilling of Tungsten Carbide Using Microelectrode with High Aspect Ratio to Improve MRR, EWR, and Hole Quality

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- MRR and EWR
- Surface roughness
- Micro-crack
- Material migration

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Acknowledgment

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### 1.10.1 Introduction

According to the CRIP committee of physical and chemical processes, micro-machining is considered as one of the most fundamental technologies to manufacture and miniaturize products and parts with a dimension between 1 and 999 µm. Miniaturized products and parts are mainly used in biotechnology, information technology, environmental, medical industries, electric devices, miniaturized machines, and so on. With the recent advancements in Microelectro Mechanical System, micro-machining is being more and more popular day-by-day. A lot of studies have already been done about the fabrication of functional micro-structure and component. Basically, micromachining has been classified into three processes including conventional material removal processes, non-conventional material removal processes, and hybridized processes.

### 1.10.2 Material Removal Processes

#### 1.10.2.1 Conventional Process

Mechanical force and energy are required for conventional material removal processes where shear force removes the material. Shear refers to simple machining process by physical contact between material and cutting tools. Traditional material removal processes such as micro-turning, micro-milling, micro-drilling, and grinding use a single-point diamond cutter or very fine-grit-sized grinding wheels to produce machine parts. They can be used for machining of the most of the materials; for example, ferrous and non-ferrous metals, semiconductors, and plastics. The products with any shape such as flat surfaces, arbitral curvature, long shaft, and so on can be fabricated by conventional material removal processes. Figure 1 presents the experimental setup for micro-turning, micro-milling, and micro-grinding.

#### 1.10.2.2 Nonconventional Process

In the nonconventional process, other sources of energy such as light energy, spark energy, vibration energy, electrolysis energy, energy beams (laser beam, electron beam, or ion beams), mechanical energy (based on erosion mechanism), etc., are used to remove the material. Techniques based on energy beams (beam-based micromachining) or solid cutting tools (tool-based micromachining) can be used for micro-machining. There are some constraints due to poor control of 3D structures, low material removal rate (MRR) and low aspect ratio in the beam-based micro-machining by using the laser beam, ion beams, or electron beam. Furthermore, special facilities are required for these processes and the maximum achievable thickness is relatively small. Also, due to its quasi-three-dimensional structure, there are some limitations in using photolithography on silicon substrates includes its low aspect ratio and limitation of the work material. High aspect ratio of three-dimensional submicron structures by very high form accuracy can be produced deep X-ray lithography using synchrotron radiation beam (LIGA) process and focused-ion beam machining process. While the special facilities are required for these processes and the
Figure 1

(a) Micro-turning setup, (b) Close view of the micro-milling experimental setup, (c) Micro-grinding system setup.

1. Piezoelectric Dynamometer
2. Encoder drive
3. Variable frequency drive
4. Servo motor with encoder
5. Spindle with inbuilt motor
6. Micrometer
7. Coated carbide tool
8. Tool holder
9. Dial gauge

Table 1

<table>
<thead>
<tr>
<th>Corner Geometry</th>
<th>Symbol</th>
<th>Units</th>
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<tr>
<td>Coating</td>
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<td>MS-(AlTi)N</td>
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<tr>
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</tr>
<tr>
<td>Shank diameter</td>
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<tr>
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<td>- 2</td>
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</table>


Figure 1  (a) Micro-turning setup, (b) Close view of the micro-milling experimental setup, (c) Micro-grinding system setup.
maximum thickness is relatively small.\cite{15,16} Figure 2 illustrates the photographic view of the CNC-pulsed Nd:YAG laser machining system\cite{17} and schematic diagram of experimental setup for laser micro-milling process,\cite{18} cover plate laser beam machining (c-LBM),\cite{19} laser induced plasma micro-machining,\cite{20} focused ion beams (FIB) system,\cite{21} and gas cluster ion beam irradiation system for precision machining.\cite{22}

1.10.2.3 Hybridized Process

Hybridized processes are basically a combination of conventional material removal processes (like turning and milling) and non-conventional (such as electrical discharge machining (EDM), wire electrical discharge grinding (WEDG), and electrical discharge grinding (EDG)) to make microstructures with high accuracy. The hybrid material removal process can produce micro-components with almost all kinds of the material, such as metal, plastics, and semiconductors. It can be machined with no limitation of shape; for instance, flat surface, arbitrary curvatures, and long shaft that are needed for the moving parts and guiding structures.\cite{23,24,25,26} The hybrid machine which includes microturning, micromilling, micro-EDM, wire electrical discharge machining (micro-WEDM), micro-WEDG, and on machine measurement equipment is shown in Figure 3.

1.10.3 EDM and Micro-EDM Processes

1.10.3.1 Electrical Discharge Machining

EDM is a nonconventional machining process that removes electrical conductive materials according to the thermal energy (melting and partial vaporization of the workpiece) produced by series of sparks occurring between the electrode and workpiece.\cite{27,28,29,30} The EDM process is potentially useful for machining materials with various hardness, complex shapes, strength, temperature-resistant, fine surface finish, and accurate dimensions.\cite{27,28,29,30,31,32,33}

Figure 4(a) illustrates that each spark occurs between the workpiece and the closest points of the electrode. The material is removed from both the electrode and workpiece by the spark, which results in an increase of the distance between the electrode and the workpiece at that point. This causes the next spark to occur at the next-closest points between the electrode and workpiece as shown in Figure 4(b). As also can be seen in Figures 4(a) and 4(b), the electrode and workpiece surfaces are quite rough. In fact, all surface finishes have irregular surfaces. Even though the surfaces have only very minute peaks and valleys, these very small changes of dimension allow the EDM spark to occur between the closest peaks.\cite{34}
In EDM, the flow of electricity between the electrode and workpiece introduce the heat in the form of a spark. The main characteristic of the dielectric fluid is that it works as an electrical insulator, until enough voltage is applied to cause it to change into an electrical conductor. The dielectric fluid deionizes when the spark is turned off and the fluid returns to being an electrical insulator. For each spark, this change of the dielectric fluid from an insulator to a conductor, and vice versa occurs as shown in Figure 5.34

A small amount of the electrode and workpiece material is vaporized with each spark. The vaporized material is placed in the sparking gap between the workpiece and the electrode in the form of a cloud. The vaporized cloud solidifies when the spark is turned off. Each spark then produces a very tiny hollow sphere of material known as EDM chip (debris) made up of the electrode and workpiece material. Figure 5 illustrates the spark producing the vapor cloud, the cloud in suspension, cloud being cooled and forming into an EDM chip, and removing the chip by flowing dielectric.34

The EDM chip must be removed from the sparking area for efficient machining. This removal is performed by flowing dielectric fluid through the sparking gap. Part of the EDM chip is removed by the dielectric fluid and the remaining part solidifies on the electrode surface. As a result, each discharge produces a small crater on both workpiece and tool electrode.35

### 1.10.3.2 Sparking and Gap Phenomena in EDM

Rajurkar et al. and Kunieda et al. reveal that the steps of gap phenomena include the formation of plasma in the dielectric, electrons and ions interaction, heat transfer and material removal by melting and vaporizing, solidified the melting and vaporizing material to debris (chip), flushing the debris, and another spark generation as schematically illustrated in Figures 6(a)–6(c).36,37

Figure 6(d) presents a schematic view of the discharge spot. The arc column diameter is considered to increase with the passage of time and equal to the diameter of the generated discharge crater. Electrode materials and dielectric liquid are evaporated, molecules are dissociated, and atoms are ionized, resulting in a rapid expansion of the bubble. As the expansion is confined by the viscosity and inertia of the dielectric fluids, the remaining inside pressure of the bubble gets extremely high level and the boundaries between the bubble and liquid get expanded with the several 10 m s⁻¹ of velocity order. It is yet considered that the dielectric liquid has a significant role in the material removal process as the dynamics of the material removal in EDM depends on the high velocity and pressure development in the bubble.36

After the end of the discharge duration, ions and electrons are recombined and the dielectric breakdown strength is recovered. The evaporated atoms and molecules are solidified or...
condensed to form debris particles or dielectric liquid, but gases such as hydrogen and methane which are generated by the dissociation of the working oil are left to form a bubble. Since pulse discharge occurs several thousand times or more per second, obviously the gap becomes filled with gas in typical EDM processes. Hundreds of debris particles are generated per single pulse discharge. Melted and evaporated materials are cooled by the dielectric liquid and solidified to form spherical debris particles. Thus, debris particles are removed from the gap with the dielectric liquid and not reattached on the workpiece and electrode surfaces. Furthermore, heat convection in the boundary layers of the dielectric liquid cools the workpiece and electrode surfaces, resulting in machining stability. Thus, the dielectric liquid plays another important role in flushing debris particles and cooling of the gap.\endnote{272}

1.10.3.3 Function and Types of Micro-EDM Process

Micro-EDM and EDM have same characteristics but only the size of electrode, discharge energy, and resolution of movement in axis are at the micron level in micro-EDM.\endnote{6} The principle functions of the micro-EDM process are micro-mold making, production of die and cavities, and complex three-dimensional shapes in the micron size.\endnote{38} In EDM and micro-EDM, no direct contact and negligible force between the workpiece and tool cause to elimination of deformation on the tool, chatter, mechanical stress, and vibration errors during machining.\endnote{6,35,40}

A micro-mold cavity has function in mass production of a microcomponent which can be produced by injection molding. Hard-to-machined materials are used for micro-injection that should be machined very accurately and complex shape in three-dimensional forms in the micron range.\endnote{43-45} Micro-EDM is one of the effective alternative machining processes that can be used successfully in the production of complicated three-dimensional models using very hard die materials.\endnote{1,6,35,40} Besides, it is also possible to use for very high-precision machining of the curved surface, slope surface, and thin-sheet materials that are difficult for machining.\endnote{1,6,35,41,42} Moreover, a conductive material with any hardness can be machined by micro-EDM without any force. So, micro-mold can be fabricated by using a very thin electrode with controlling of the EDM contour.\endnote{2-5}

According to Jahan et al.,\endnote{43} current micro-EDM technology schematic is shown in Figure 7, is used for manufacturing micro-features can be categorized into five different types are as follows:

- **Die-sinking micro-EDM**: where a microelectrode is used to fabricate its mirror image in the workpiece.
Micro-wire EDM, in which a wire of diameter less than 0.02 mm is employed to cut through a conductive workpiece.

Micro-EDM drilling, where microelectrodes are used to ‘drill’ micro-holes in the workpiece.

Micro-EDM milling, where microelectrodes are employed to produce 3D cavities by adopting a movement strategy similar to that in conventional milling.

During micro-EDM, the micro-EDG process is employed to fabricate the microelectrodes on the micro-EDM machine.

- Micro-wire EDM
- Micro-EDM drilling
- Micro-EDM milling
from a thicker electrode. Different setup and trajectory control of the electrode can be employed in this process included using a ‘stationary block,’ ‘rotating disk,’ ‘wire EDG (WEDG),’ etc.

1.10.3.4 Pulse Generators/Power Supply

Transistor-type pulse generator and resistance capacitance (RC) (relaxation-type) are the two major types of EDM power supply (Figure 8). Among these two types, RC-based power supply has gained extensive usage in micro-EDM. Moreover, transistor-type power supply has been employed for the power supply of the conventional EDM.36,45–47

1.10.3.4.1 Transistor-type pulse generator

A series of transistors and resistances are connected in parallel between the direct current power supply and the discharge gap in a transistor-type power supply as shown in Figure 8(a). The discharge current flow increases proportionately with the number of transistors switched on at the same time. The Field-effect transistor (FET) operates the gate control circuit by switching it ON or OFF. While generating a single pulse, the gap voltage is monitored to detect the discharge phenomena and the FET is turned OFF after the preset discharge duration.45

Transistor-type pulse generators can change the discharge current and the pulse duration based on the required machining characteristics. It provides a very uniform pulse shape resulting in much better control of surface roughness. The resistance across the circuit and the input voltage (R and Vcc in Figure 8(a)) control the discharge energy in every spark.45 The smallest UR is obtained by increasing the resistance at around 60 V with voltage settings in transistor-type power supply. If the voltages get lower than 60 V, it will result in unstable discharges.35–37 It is difficult to minimize the UR frequency because of micro-EDM is fundamentally a discontinuous material removal process but the UR could be minimized significantly by increasing the resistance. The transistor-type pulse generator controls the sparks using microcontroller (decision-making process of the electronics). The micro-controller sets pulse-ON time, pulse-OFF time, signal propagation delay, and the inherent delay of the power transistor. Very fast electronics are used in the setup as all those processes contribute more than few hundred nanoseconds.36,45,48 This imposes a limit on the shortest pulse duration.45 Jameson44 stated that “spark energy is determined by the amount of electrical power contained in each spark, multiplied by the amount of time the electrical power is flowing.” The equation for determining spark energy is:

\[ E = V \cdot I_p \cdot t_{ON} \]  [1]

where, \( V \) = voltage, \( I_p \) = current of a single pulse, and \( t_{ON} \) = pulse-ON time.

1.10.3.4.2 RC-type pulse generator

Figure 8(b) shows schematic of basic circuit diagram for RC-type pulse generator. Discharge pulse duration in an RC- or relaxation type circuit is dominated by the capacitance of the capacitor and the inductance of the wire connecting the capacitor to the tool and workpiece37,45,49 and the spark energy (discharge energy) is specified by the used capacitor. The charging and discharging cycle of the capacitor takes place repeatedly.

The capacitor (C) is charged during the charging cycle through the resistor (R) and discharged between the electrode and workpiece during the discharging cycle. The pulse energy \( E \) induced in the gap can be calculated by the following formula;14,45,46 the gap voltage \( V_g \) is assumed to be constant during the discharging cycle.

\[ E = 2CV_g(V - V_g) \]  [2]

In this equation, the discharge capacitance is denoted by \( C \) and \( V \) is the supplied DC voltage. The maximum discharge energy is produced when \( V = 2V_g \). The value of maximum discharge energy is 0.5CVg, which is equal to the energy stored in the capacitor. In a real application, the RC-type pulse supply will have a stray capacitance between the electric feeders, tool electrode holder, and the work table and the tool electrode and the workpiece. Therefore, the modified form of the above equation is given below45:

\[ E = 2(C1 + C2)V_g(V - V_g) \]  [3]

According to the eqn [3], the minimum achievable discharge energy per pulse is determined by the stray capacitance \( C2 \) provided that the value of discharge capacitance \( C1 \) is 0. Therefore, it is important to reduce the stray capacitance between the wire and the workpiece in order to decrease the spark energy. A minimum discharge energy is needed in the finishing (final stage of machining) or while machining features at the lower boundary of micro-machining domain.45,49 It can easily produce pulses with high-peak current and short duration which cause to achieve required surface finish with efficient and accurate material removal. On a properly designed equipment, the stray capacitance could be kept as small as around 10–12 pF delivering 0.2-mA peak current and 30-ns wide pulse.45,50

Figure 8 Schematic representation of basic circuit diagram of (a) transistor-type and (b) RC-type pulse generator.45
The discharge frequency (discharge repetition rate) depends on the charging time, that is determined by the circuit resistor (R) and this provides for an additional advantage of the RC power supply: when the capacitance is reduced, it also reduces the capacitor charging-up time following a first-order differential equation. The time taken for full charging-up of a capacitor can be calculated by $5 \times RC$ and while $R = 1 \text{k}\Omega$ and $C = 10 \text{pF}$, the full charging time of the capacitor is around 50 ns. Therefore, the value of 'R' should not be very low as arcing can occur instead of sparking and critical resistance that will prevent arcing is desirable.\textsuperscript{45,51}

However, the use of RC pulse generator in machining usually results an extremely low MRR. This is due to the fact that the energy per spark is reduced significantly as it depends on the uncontrolled spontaneous discharge frequency bottlenecked by the required capacitor charging time. Moreover, it is difficult to obtain uniform surface finish as the discharge energy varies by depending on the stored electrical charge in the capacitor before dielectric breakdown. In addition, the workpiece can easily be thermally damaged, if the dielectric strength was not properly recovered after the previous discharge and the current continued to flow through the same plasma channel in the gap without charging the capacitor.\textsuperscript{45,48}

The basic reason of still using RC-type power supply in micro-EDM is the fact that the charging time for a very small capacitor is much smaller, around few tens of nanoseconds, than the smallest duration of the OFF time that can be reliably achieved using a transistor-type power supply designed using available electronic components. Besides, a transistor power supply would occupy additional time around few tens of nanoseconds for the discharge current to be diminished to zero while an immediate active control of power supply is needed upon short circuit detection. Therefore, the existing high current may pass through the circuit in this additional time and causes damage to fine feature that will be machined in the workpiece.\textsuperscript{45}

### 1.10.3.4.3 Pulse waveform and discharge energy

The pulse generator type determines the discharge energy and pulse shape for the micro-EDM. Figures 9(a) and 9(b), demonstrate the ideal voltage and current signals for transistor and RC-type pulse generator respectively. The spark energy (discharge energy) of a pulse generator is calculated by its electrical and discharge parameters. MRR, electrode wear ratio (EWR), and surface roughness increase with amplifying of discharge energy.\textsuperscript{45} Though used pulse shape in micro-EDM is generally rectangular type, but generators using other pulse shapes have also been developed for various applications.\textsuperscript{45,52}

For instance, EWR decreased to very low values by initiating trapezoidal pulse shapes in micro-EDM.\textsuperscript{45,53}

The open voltage is applied between the tool electrode and the workpiece when the transistors are switched on in the transistor-type pulse generator. But the discharge does not occur instantly. It occurs after the ignition delay time and a discharge current ($I_p$) is passed through the gap after the dielectric breakdown. The transistors are kept on by the gate control circuit during the discharge time, $t_{on}$, resulting in a uniform discharge crater size. The transistors are again switched on after the fixed discharge interval $t_{off}$, while the open voltage is applied between the electrodes.\textsuperscript{34,36,45} Equation [1] can be used to calculate the discharge energy per single pulse.

![Figure 9](image-url)  
Ideal voltage–time (top) and current–time (bottom) characteristics curve/waveform for (a) transistor-type and (b) RC-type pulse generator.\textsuperscript{45,54-58}
The capacitor charging time is considered as the pulse interval or pulse-OFF time, whereas the discharging time is assumed as the pulse-ON time in the RC pulse generator. One of the major characteristics of RC-type pulse generator is that the charging voltage is higher than the breakdown or discharging voltage (V). As a result, sometimes discharging starts before the capacitor is fully charged,\(^5\), which generates nonuniform discharge energy. A simplified form of the discharge energy per single pulse, \(E\), can be calculated by eqn [2] where \(V = 2V_0\)

\[
E = \frac{1}{2}CV^2
\]

where \(C\) is the capacitance used for machining and \(V\) is the discharge voltage.\(^5\),\(^6\)

### 1.10.3.5 Electrode Material for EDM

Jameson\(^3\) stated that "electrode materials for EDM must be electrically conductive. However, they should have features such as: high melting point, an ability to be easily machined and low cost.". No single electrode material provides all of the desired features for any particular application. The following list of materials is intended as a guide to electrode materials commonly used for die-sinking machines.

#### 1.10.3.5.1 Copper

As Jameson\(^3\) stated "copper is readily available and normally specified as electrolytic-grade or tellurium-copper alloy," Electrolytic grade may be considered as pure copper. Tellurium copper is copper with the element tellurium added and it is equivalent in machinability to free-machining brass. Copper is difficult to grind but has good no-wear-machining characteristics. It is often used for RC power supply operations. Wang and Lin\(^6\) stated that "copper was chosen as electrode for electrical discharge machining of copper tungsten." The physical properties of copper that used by Che Haron\(^1\) are shown in Table 1.

#### 1.10.3.5.2 Copper tungsten

Copper–tungsten (CuW) composite is a one kind of self-cooling which is highly resistant to heat corrosion. Phasing can be seen between tungsten and copper in the microstructure of CuW composites because of tungsten and copper have no solid solubility with each other.\(^6\),\(^7\),\(^8\) Therefore, CuW composites can be considered as composite material and they are not alloys. CuW composites cannot be created through traditional metal-casting processes and are currently produced through powder metallurgy because of large dissimilation between the melting points of tungsten and copper. Powder metallurgy is gained by compacting pure tungsten powder in a mold (porous), then sintering it under high temperatures and infiltration of liquid copper.\(^6\),\(^7\),\(^8\) CuW composites have a high-melting point, corrosion, and abrasion resistance, and act as good conductors for both current and heat.\(^6\),\(^7\) CuW composites possess a very high-melting point with promising corrosion and abrasion resistance, and a good conductor of electricity and heat.\(^6\),\(^7\) The Specification of copper tungsten is shown in Table 2.

Jameson\(^3\) stated that "CuW is often used as an electrode for EDM of tungsten carbide." Lee and Li\(^6\) used copper tungsten as an electrode during the machining of tungsten carbide. Moreover, Soni and Chakraverti\(^7\) found that chemical composition of high-carbon high-chromium die steel (hardened) was changed during EDM machining with rotating copper tungsten (W80, Cu 20) electrode because of the material migration from the electrode. The result of this experiment showed that the migration of tungsten from the tool electrode to the workpiece was higher in blind holes machining rather than in through holes machining. The properties of electrode material are given in Table 3.\(^6\),\(^8\)

#### 1.10.3.5.3 Graphite

Lee and Li\(^6\) used graphite as their electrode material to identify with the comparisons between others electrode in

### Table 1

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical resistivity ((\mu\Omega\ \text{cm}^{-1}))</td>
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</tr>
<tr>
<td>Electrical conductivity compared with silver (%)</td>
<td>92</td>
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<tr>
<td>Thermal conductivity (W m K(^{-1}))</td>
<td>268–389</td>
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<tr>
<td>Melting point ((^\circ)C)</td>
<td>1083</td>
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<tr>
<td>Specific heat (cal g(^{-1})\cdot\text{g}^{-1})</td>
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<tr>
<td>Specific gravity at 20(^\circ)C (g cm(^{-3}))</td>
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</tr>
<tr>
<td>Coefficient of thermal expansion ((\times 10^{-6})\cdot\text{C}^{-1})</td>
<td>6.6</td>
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### Table 2

<table>
<thead>
<tr>
<th>Code No.</th>
<th>Chemical composition %</th>
<th>Mechanical properties</th>
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<td></td>
<td>Cu</td>
<td>Impurity</td>
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<td>CuW(50)</td>
<td>50 ± 2.0</td>
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</tr>
<tr>
<td>CuW(55)</td>
<td>45 ± 2.0</td>
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</tr>
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<td>CuW(60)</td>
<td>40 ± 2.0</td>
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<tr>
<td>CuW(65)</td>
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<td>CuW(70)</td>
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<td>CuW(75)</td>
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<td>CuW(80)</td>
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</tr>
<tr>
<td>CuW(85)</td>
<td>15 ± 2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>CuW(90)</td>
<td>10 ± 2.0</td>
<td>0.5</td>
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</table>
limited range of applications because of its high cost and limited availability.71

### Table 5 Properties of WC–6%Co75

<table>
<thead>
<tr>
<th>Grain size (in micron size)</th>
<th>Fine</th>
<th>Medium</th>
<th>Coarse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, HRA</td>
<td>92.5–93.1</td>
<td>91.7–92.2</td>
<td>90.5–91.5</td>
</tr>
<tr>
<td>Density, g cm⁻³</td>
<td>15.0</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Transverse strength, MPa</td>
<td>1790</td>
<td>2000</td>
<td>2210</td>
</tr>
<tr>
<td>Compressive strength, MPa</td>
<td>5930</td>
<td>5450</td>
<td>5170</td>
</tr>
<tr>
<td>Modulus of elasticity, GPa</td>
<td>614</td>
<td>648</td>
<td>641</td>
</tr>
<tr>
<td>Relative abrasion resistance</td>
<td>100</td>
<td>58</td>
<td>25</td>
</tr>
<tr>
<td>CTE, ppm K⁻¹</td>
<td>4.3</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>CTE, ppm K⁻¹, at 1000 °C</td>
<td>5.9</td>
<td>5.4</td>
<td>5.6</td>
</tr>
<tr>
<td>Thermal conductivity, W m⁻¹ K⁻¹</td>
<td>_</td>
<td>100</td>
<td>121</td>
</tr>
</tbody>
</table>

### 1.10.3.5.8 Tungsten

Tungsten (W) had been the electrode material of choice for certain limited EDM applications due to the combination of its high density, melting point, and tensile strength. Tungsten has poor electrical conductivity which causes to cut much slower than copper or brass. Also, tungsten is seldom used because of its high cost and very low machinability.71

### 1.10.3.5.9 Tungsten carbide–cobalt (WC–Co)

Tungsten carbide (WC) and its composite (WC–Co) are employed for producing cutting tools, dies, and other special tools and components owing to their high hardness, strength, wear, and corrosion resistance over a wide range of temperatures.72,73 Also, they can be used as electrode for EDM.3,74 Table 5 illustrates the properties of WC–6%Co.

### 1.10.3.6 Electrode Material for Micro-EDM

The thermal property of the electrode materials has significant influence on the micro-EDM performance as micro-EDM is a thermal process. The electrode with higher heat conductivity has lower temperature on its surface when the heat fluxes from the arc column are equal.36 Therefore, the materials with higher heat conductivity, melting point, and boiling point are appropriate as microelectrodes. The important properties of the electrode materials, which influence on the micro-EDM process, include melting and boiling temperatures, electrical and thermal conductivity, and specific heat.34,35,57 Table 6 demonstrates what kind of materials as microelectrode was used by previous researchers for machining of various materials.

According to Jahan et al.,77 between AgW, CuW, and W electrodes for micro-EDM of WC, AgW electrode produces smoother and defect-free nanosurface with the lowest Ra and Rmax among the three electrodes. Besides, a minimum amount of material migrates from the AgW electrode to the WC workpiece during the finishing micro-EDM. On the other hand, a CuW electrode achieves the highest MRR followed by AgW and W. In the case of electrode wear, the W electrode has the lowest wear followed by CuW and AgW.
Table 6  Materials of microelectrode for machining various workpieces

<table>
<thead>
<tr>
<th>Materials of microelectrode</th>
<th>Materials of workpiece</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper tungsten (CuW)</td>
<td>WC 10 wt.%Co</td>
<td>57</td>
</tr>
<tr>
<td>Silver tungsten (AgW)</td>
<td>A block of Uddeholm Stavax ESR tool steel</td>
<td>76</td>
</tr>
<tr>
<td>Tungsten (W)</td>
<td>Nickel–titanium-based shape memory alloy (SMA) with 500 μm thickness</td>
<td>77</td>
</tr>
<tr>
<td>Tungsten carbide</td>
<td>Titanium alloy (Ti-6Al-4V)</td>
<td>78</td>
</tr>
<tr>
<td>Brass</td>
<td>SiC microparticle suspended dielectric on machining Ti-6Al-4 V</td>
<td>79</td>
</tr>
<tr>
<td>Tungsten carbide</td>
<td>Inconel 718 alloy</td>
<td>80</td>
</tr>
<tr>
<td>Tungsten</td>
<td>RB-SiC material composed of 6H–SiC grains (grain size 1 μm, 88% in volume) and a Si matrix (12% in volume)</td>
<td>81</td>
</tr>
</tbody>
</table>

1.10.3.7  Dielectric Medium in EDM

Basic characteristics required for dielectric used in EDM are high-dielectric strength and quick recovery after breakdown. Sommer stated that “dielectric fluid performs three important functions:

1. The fluid forms a dielectric barrier for the spark between the workpiece and the electrode.
2. The fluid cools the eroded particles between the workpiece and the electrode.
3. The pressurized fluid flushes out the eroded gap particles and removes the particles from the fluid by causing the fluid to pass through a filter system.”

The selection of a dielectric fluid is subject to certain conditions as follows:

1. It must be capable of being ionized at a consistency voltage so that its performance is predicted.
2. It must be able to deionizer so that it becomes an efficient insulator during his next build-up of the discharge.
3. There must be no dermatitis.
4. There should be no toxic fumes or excessive smoking.
5. The fluid should inhibit corrosion.
6. The flashpoint of the fluid should be high.
7. The fluid must have low viscosity.

1.10.3.7.1  Mineral oil

Mineral oil or liquid petroleum is a by-product in the distillation of petroleum.

1.10.3.7.2  Kerosene

Kerosene was one of the first popular dielectric oils. Its primary benefit is that it has very low viscosity and flushes very well. Unfortunately, it has many drawbacks like low-flash point, high volatility, odor, and skin reactions. In the ‘old days,’ there were numerous EDM fires and explosions attributed to the use of kerosene.

1.10.3.7.3  Mineral seal

The name mineral seal oil refers to the fact that it has been derived from sea seal blubber for using in signal lamps and light houses. Mineral seal oil is basically petroleum oil which has many industrial applications. For example, this oil was used as a dielectric fluid in EDM by a number of aerospace companies. In fact, it is listed as potential aerospace dielectric oil in recent times. Unfortunately, it contains some potentially carcinogenic elements, and its use is no longer recommended.

1.10.3.7.4  Transformer oil

Transformer oil is another type of mineral oil-based product which was tailored to be used in EDM as dielectric. Earlier generations of transformer oil were compounded with PCBs. However, transformer oil is not currently being used in EDM.

1.10.3.7.5  Water-based dielectrics

Water is a dielectric fluid which can be used as an alternative to hydrocarbon-based oils. This approach is important to promote a healthy and safe environment while using water in EDM machining. Contemporarily used hydrocarbon oils (i.e., kerosene) release toxic vapor (CO and CH₄) after being decomposed. Research has been carried out over the last 25 years which involves the use of pure water and water with additives. Leao and Pashby reported that many works have already been carried out to evaluate the feasibility of adding organic additives such as ethylene glycol, polyethylene glycol 200, polyethylene glycol 400, polyethylene glycol 600, dextrose, and sucrose to improve the properties as well as performance of demonized water as dielectric.

1.10.3.7.6  Powder-mixed EDM

The working principle of powder-mixed EDM (PMEDM) is completely different from the contemporary EDM machining process. An appropriate material in the powder form is mixed into the EDM dielectric. When a suitable voltage is applied, the spark gap filled up with powder particles and the gap distance setup between tool and the work piece increased. The powder particles get energized and act in a zigzag fashion as illustrated in Figure 10. These energized particles are accelerated by the supplied electric field and behave as electric conductors. The charged powder particles arrange themselves in clusters beneath the sparking area. This chain formation of charged particles in the dielectric helps to bridge the gap between electrode and workpiece which is responsible for the early explosion. Thus, faster sparking (discharge) takes place and faster erosion from the workpiece surface occurs. Adding aluminum powder in the dielectric results in increased MRR and improved surface roughness during EDM.


1.10.3.7.7 Dry EDM
In dry EDM, a thin-walled pipe works as tool electrode through which high-pressure gas or air is flown. The high-pressure gas flow to remove the debris from the gap and cools down the inter electrode gap. The technique was invented to decrease the pollution caused by the use of dielectric fluid which leads to production of vapors during machining and the cost to manage the waste.\(^6\)

1.10.4 EDM and Micro-EDM Process Parameters

EDM parameters are categorized into two groups:

1. Electrical parameters:
   - Polarity of the electrode
   - Machining voltage
   - Current
   - Pulse-ON time (duration or pulse time)
   - Pulse-OFF time (non-load voltage or pause time)
   - Duty factor
   - Capacitor.

2. Non-electrical parameters:
   - Flushing pressure of dielectric
   - Rotating speed of the electrode.

The electrode polarity, machining voltage, current, pulse-ON time, pulse-OFF time, duty factor, flushing pressure of dielectric, and rotating speed of the electrode are the parameters used in transistor-type pulse generator while the electrode polarity, machining voltage, capacitor, flushing pressure of dielectric, and rotating speed of the electrode are the parameters used in RC-type pulse generator. As mentioned before, RC-based power supply has gained extensive usage in micro-EDM.\(^{36,45-47}\)

The electrode polarity: Electrical polarity of the electrode and workpiece determines the direction of flow for electrons and positive ions. Some EDM manufacturers describe electrode and workpiece polarity as standard and reverse. This description is not acceptable since not all manufacturers use the same polarity for standard and reverse. Because of this, most manufacturers have revised their electrode and workpiece polarity description to specify only electrode polarity as either negative or positive. It is understood, when using this description, that the workpiece is the opposite polarity of that specified for the electrode.\(^5\)

The electrons usually are emitted from the cathode (negative polarity) and move toward the anode (positive polarity) during the micro-EDM process. After that, the metal ions are removed from the anode material due to the electrons which reach the anode surface strike the anode surface. Hence, more materials are removed from the anode’s surface rather than the cathode’s surface. This is the main reason for earning high MRR when the polarity of electrode is negative during micro-EDM of workpiece with positive polarity.\(^5\)

Discharge voltage: Discharge voltage in the EDM process depends on the spark gap and breakdown dielectric strength. Before flowing electricity, the open gap voltage gets increased till the ionization path is created through the dielectric. As soon as the current starts to flow, the voltage decreases and stabilizes at the working gap level. The predetermined voltage sets the spark gap width between the leading edge of the electrode and workpiece. A higher voltage setting augments the gap, which improves the flushing conditions and helps to stabilize the cut. As the electric field strength improves, tool wear rate (TWR) of MRR and surface roughness amplifies with increasing the open-circuit voltage. However, the after machining effect of varying the open-circuit voltage on surface hardness has been found to be marginal.\(^6\)

Peak current: Peak current is the amount of power used in discharge machining and the ampere (A) is its unit. The current is the most important machining parameter in EDM. During each pulse-ON time, the current amplifies until it reaches a preset level, which is expressed as the peak current, with the augmentation of the current, MRR and electrode wear increase and surface finish deteriorates.\(^39,52\)

Pulse-ON time (duration or pulse time): Pulse-ON time is the time duration that the current is allowed to flow per cycle. Material removal is directly proportional to the amount of energy applied during this pulse-ON time. The spark energy (discharge energy) is controlled by the pulse-ON time and peak current.\(^54\)

Pulse-OFF time (non-load voltage or pause time): Pulse-OFF time is the time duration between the sparks (pulse-ON time). Pulse-OFF time allows the molten material to solidify and to remove debris from the distance between electrode and workpiece (arc gap). This parameter is to affect the speed and the stability of the cut. Thus, using the too short pulse-OFF time causes the sparks to be unstable.\(^54\)

Duty factor: Duty factor is calculated based on following equation.\(^55\)

\[
\text{Duty factor} = \frac{\text{Pulse-ON time}}{\text{Pulse-ON time} + \text{Pulse-OFF Time}} \times 100\% \quad [5]
\]

Capacitor: The capacitor stores the electrical energy and discharges during the machining. When machining starts as soon as the dielectric breaks down, it discharges the charge stored in the capacitor.\(^56\)

Flushing of dielectric fluid: The dielectric fluid is utilized to flush through the spark gap (the distance between electrode and workpiece) to remove debris (chip) during machining and to keep the dielectric temperature below its flash point.\(^52\)

The dielectric flushing during the sparking process has an effect on the EDM performance measures. The flushing during the roughing step influenced the MRR and EWR, while in the finishing step, it influenced the surface roughness. The flushing rate also affects the recast layer and crack density, which can be minimized by obtaining an optimal flushing rate. Moreover, the different properties of the dielectric fluid also play a vital role in flushing away the debris from the machining gap. MRR and
EWR are dependent on the conductivity, breakdown resistance, viscosity, flash point, and safety factors of the dielectric fluids.\textsuperscript{22} The rotating speed of the electrode: The tangential velocities of the electrode amplifies with increasing of the electrode rotating speed, which causes to the dielectric disturbance.\textsuperscript{27} The augmentation of the dielectric flow speed helps to remove and flash out debris between the electrode and workpiece (the machined zone). Therefore, it causes to remove higher material from the workpiece.\textsuperscript{24}

1.10.4.1 EDM Performance Measure (Machining Characteristics)

1.10.4.1.1 MRR
MRR is calculated based on the volume of material removed from the workpiece divided by machining time.\textsuperscript{25}

\[
MRR = \frac{\text{Volume of material removed from workpiece}}{\text{Time of machining}} = \frac{W_b - W_a}{t_m} \quad \text{(g min}^{-1})
\]

where \(W_b\) is the weight of workpiece material before machining (g), \(W_a\) is the weight of workpiece material after machining (g), and \(t_m\) is the machining times (min).

1.10.4.1.2 EWR
EWR is calculated based on the percentage of volume of material removed from the electrode divided by the volume of material removed from the workpiece.\textsuperscript{35}

\[
EWR = \frac{T_b - T_a}{W_b - W_a} \times 100\% \quad \text{(7)}
\]

where, \(T_b\) is the weight of electrode material before machining (g), \(T_a\) is the weight of electrode material after machining (g), \(W_b\) is the weight of workpiece material before machining (g), and \(W_a\) is the weight of workpiece material after machining (g). Figure 11 illustrates different kinds of electrode wear including: (1) corner wear, (2) end wear, (3) side wear, and (4) volumetric wear\textsuperscript{34}.

1.10.4.1.3 Surface roughness
The surface finish is controlled by the number of discharges per second, more often referred to as the frequency sparks. The greater amount of energy applied the greater amount of material removed. However, when greater amounts of current are used larger craters are eroded from the work, causing a rougher surface finish. To maintain increased metal-removal rates and at the same time improve the surface finish, it is necessary to increase the frequency of the discharges. Surface integrity involves the measures of surface roughness, heat affected zone, micro-hardness, micro-crack, residual stress, diffusion of tool material and carbon, and endurance limit.\textsuperscript{38}

1.10.4.2 Micro-EDM Performance Measure (Machining Characteristics)

1.10.4.2.1 MRR
Micro-EDM produces the reverse-copied shape of the micro-electrode in the workpiece. Figure 12 illustrates the relationship of the micro-hole shape with an microelectrode feed. It is possible the micro-holes shapes were not confirmed because of the microelectrode wear if the microelectrodes did not feed enough. In order to achieve the acceptable micro-holes shape, it is essential to feed the microelectrodes several times as long as the workpiece thickness.\textsuperscript{40}

In fact, it is usual to measure the weight differences and convert them into volumes by the materials density. But, this method is inappropriate for micro-EDM as the removed materials is so small (about less than 10 ng) that it is difficult to measure it accurately. So, it is important to measure and calculate removed volume of materials directly.\textsuperscript{40} The micro-hole is not an ideal cylindrical one but a tapered one because of the debris moving and the second discharge on the side of micro-hole.\textsuperscript{96} MRR is calculated by following equation (the geometry is shown in Figure 13).\textsuperscript{36}

\[
MRR = \frac{\frac{2}{3} \left( r_{\text{Top}}^2 + r_{\text{Top}} r_{\text{Bottom}} + r_{\text{Bottom}}^2 \right) \times h}{t} \quad \text{(8)}
\]

where, \(r_{\text{Top}}\) is the radius at the entrance side, \(r_{\text{Bottom}}\) is radius at exit side, \(h\) is the workpiece thickness, and \(t\) is the machining time to make a micro-hole at a particular setting.

1.10.4.2.2 EWR
Figure 14 demonstrates the different types of wear on the microelectrode. EWR refers to the ratio of amount of

![Figure 11](image1.png)

**Figure 11** The different kinds of electrode wear.\textsuperscript{24}

![Figure 12](image2.png)

**Figure 12** Influence of microelectrode feed on the shape of a micro-hole.\textsuperscript{39}
There are four different methods to determine the EWR which include measuring weight, shape, microelectrode length, and total volume respectively. A popular one is by evaluating volumetric EWR. In fact, it is a usual method to measure the weight differences and then transfer them into the volumes by the density of materials. However, this method is not suitable to evaluate EWR for micro-EDM. As the weight change of the materials in micro-EDM is so small (about less than 10 ng) that it is difficult to determine it accurately. Therefore, it is necessary to directly measure and analyze removed volume.

EWR is computed by the following equations respectively.

\[ \text{EWR} = \frac{\text{TW}}{\text{MRR}} \]  \[ \text{TW} = \pi D^2 T \frac{t}{4t} \]

where \( \text{TW} \) refers to the volumetric TWR, \( T \) refers to the frontal microelectrode wear (bottom wear), \( D \) refers to the microelectrode diameter, and \( t \) refers to the machining time to make a micro-hole at a particular setting.

The wear morphologies of the fabricated microelectrodes are illustrated in the Figure 15 after machining micro-holes on the workpiece SUS304 with the same condition. It was reported that strong wear occurs on the corner areas especially for nickel (Ni), titanium (Ti), and iron (Fe) microelectrodes because of the low thermal conductivity. Aluminum microelectrode (Al) had the melting trace after machining of SUS304 and the bending was during machining of iron. Therefore, the very low melting point aluminum has to be taken into consideration. The results show that corner rounding of the microelectrodes is strongly correlated with heat and a great amount of heat stacked at the corner would cause strong wear off.

Tsai and Masuzawa by comparing the microelectrode wears of various materials in micro-EDM found that:

a. The microelectrode volumetric wear ratio gets lower for the microelectrode material with high boiling and melting point with high thermal conductivity. This is independent phenomena for different workpiece materials.

b. Microelectrode corner wear is related to heat diffusion. Therefore, corner rounding is more obvious when the thermal conductivity of the microelectrode remains low.

c. The boiling point of the microelectrode material takes a vital role in wear mechanism of micro-EDM, as high surface temperature and energy density are related to small discharge spot.

**1.10.4.2.3 Overcut**

The micro-holes overcut were calculated from the distance between the machined micro-holes diameter and the microelectrode diameter. Due to the taper shape of the microelectrode, the overcut was calculated from the average value of the micro-holes entrance and exit side. The overcut is calculated from the following equations (Figure 13):

\[ O_c = \frac{D_h - D_s}{2} \]
and

\[
D_h = \frac{D_{\text{Top}} + D_{\text{Bottom}}}{2}
\]

where \(O_c\) is overcut of the micro-holes, \(D_h\) is the average diameter of the micro-hole after machining, \(D_t\) is the diameter of the micro-electrode, \(D_{\text{Top}}\) is the entrance diameter, and \(D_{\text{Bottom}}\) is the exit diameter of the micro-hole.

### 1.10.4.2.4 Surface integrity

Surface integrity involves two aspects: topography characteristics and surface layer characteristics. The topography characteristics are made up of surface roughness, waviness, errors of form, and flaws. The surface layer characteristics that can change through processing are: plastic deformation, residual stresses, heat affected zone, micro-cracks, micro-hardness, phase changes, and recrystallization.

### 1.10.4.3 Various Fabrication Processes of Micro-electrode

Micro-EDM is one of the most efficient technologies for fabricating micro-components between nonconventional machining technology. It can be machined ductile, brittle, or super hardened-materials with noncontact process; thus, there is little or almost no force between electrode and workpiece. For micro-EDM process. It is possible to achieve high-precision and high-quality machining with suitable parameters. It is possible to utilize a very thin and long micro-electrode for machining, because of the noncontact nature of EDM. A micro-Milling cutter of down to 50 \(\mu\)m in diameter can be found in the market. However, the length of the tool is usually three to five times of its diameter. Micro-EDM can be used to machine tough die material which micro-Milling is not appropriate to machine them. Although micro-EDM has significant role in the field of micro-machining, EWR and low MRR are some of the disadvantages of micro-EDM. Changing the micro-electrode or preparing longer micro-electrode from the beginning or fabricating the micro-electrode can compensate the wear of micro-electrode. Change the micro-electrode can reduce the accuracy to the change in setup or re-clamping of the micro-electrode; hence, it is not recommended during machining. Consequently, to avoid clamping error in micro-EDM process, micro-electrode should be fabricated on the machine. By EDM process using a sacrificial micro-electrode can be fabricated a cylindrical micro-electrode from an micro-electrode thicker than the required diameter.

The fabrication processes of micro-electrode are as follows:

1. WEDG
2. Rotating sacrificial disk
3. Stationary block electrical discharge grinding (BEDG)

---

**Table 1**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Micro-electrode material</th>
<th>Results</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>Low, ex. Ti, Fe, Ni</td>
<td>strong wear on corner</td>
<td>Ti, Fe</td>
</tr>
<tr>
<td></td>
<td>High, ex. Ag, Cu</td>
<td>little wear on corner</td>
<td>Ag, Cu</td>
</tr>
<tr>
<td>Melting point</td>
<td>Low, ex. Al</td>
<td>bending and melting</td>
<td>Al, Al</td>
</tr>
<tr>
<td></td>
<td>High, ex. W, Ta, Mo</td>
<td>little change</td>
<td>W, Mo</td>
</tr>
</tbody>
</table>
4. Moving block electrical discharge grinding (MBEDG)
5. Self-drilled micro-hole
6. Revers EDM
7. Micro-turning process
8. Hybrid process.

1.10.4.3.1 WEDG

WEDG process is known as guided running wire, and it is a typically process for micro-EDM in Figure 16. Figure 17 illustrates typical surface condition of the microelectrode is fabricated by EDM using a running wire. This method is mainly used for micro-EDM machining. The dimensional change of the electrode is theoretically zero, because of using a fresh wire continuously. High-accuracy dimensional can be achieved in micro-EDM by this fact. However, the efficiency of the surface finishing in WEDG method is lower than the rotating electrode process. Because the running wire diameter is only 0.07 mm which is not enough to smoothly finish the machined surface the same as the rotating electrode method with 0.5 mm thickness. Therefore, the speed of the finish machining should be reduced to achieve better surface finishing by using this thin wire. Figure 18 shows the schematic diagram of tangential-feed WEDG (TF-WEDG) compared with conventional radial-feed WEDG. WEDG can fabricate the microelectrode by employing a continuous wire electrode which is fed on a wire guide (Figure 18(a)).

1.10.4.3.1.1 Radial-feed WEDG

Figure 18(b) shows the conventional radial-feed WEDG process. In this process, the microelectrode is positioned to align its central axis in the direction of the symmetry axis ON of wire guide, and during the WEDG method the microelectrode feeds along the radial direction of the guide, namely the direction of axis ON (Y axis). The removal resolution of the microelectrode (the minimum thickness to be removed from microelectrode) is in direct proportion to the motion resolution of Y axis, and the diameter error of machined microelectrode is twice of the positioning error of Y axis (given radial feed $S_R$, microelectrode diameter decrease $\Delta d$, and $\Delta d = 2S_R$). Thus, the alignment error (in X-axis direction) and the positioning error affects directly the machining accuracy of the microelectrode.

1.10.4.3.1.2 TF-WEDG

The TF-WEDG process is proposed to reduce the effect of positioning error during fabricating the microelectrode in order to improve the accuracy.

1.10.4.3.1.2.1 Principle of TF-WEDG

The principle of proposed TF-WEDG method is presented in Figure 18(c). Here, the relative position of the microelectrode
and the wire guide with the Y-axis is set fixed. During the WEDG process, the microelectrode moves along the tangential X-axis direction of the wire-guide arc. In this method for given tangential feed \( S_T \) and microelectrode diameter decrease \( \Delta d' \), so that \( \Delta d' \approx 2 \cdot S_T \) which is detailed in Section 1.10.2.2. Therefore, the removal resolution of the microelectrodes gets improved, and the diameter error of the machined microelectrode can be controlled easily by keeping it lower than the positioning error. Moreover, it is easy to repeatedly achieve a consistent diameter for a number of machined microelectrodes by TF-WEDG method by fixing Y-axis position and feeding to the position D.99

1.10.4.3.1.2.2 Analysis of TF-WEDG

Figure 18(c) shows the wire guide which is designed as an arc shape, therefore it properly fits with the wire of TF-WEDG. The microelectrode feeds from the position A to the position B and then to the position C. Therefore, the microelectrode diameter gets reduced during the feeding procedure to obtain a minimum diameter of the microelectrode at the position C. Here the radius of the wire guide and the machined radius of the microelectrode are denoted by \( r \) and \( R \) respectively and the distance between the position A and the position C is denoted by \( S_T \). The microelectrodes diameter under different values of \( S_T \) can be calculated by using the following equation99:

\[
d_A = 2(\text{OA} - R) = 2\left(\sqrt{(R + r)^2 + R^2} - R\right)
\]  

[13]

The TF-WEDG experimental setup was performed by using wire guide with 1.3 mm radius (\( R \)). The relations between microelectrode diameter (\( d_A \)) and tangential-feed distance (\( S_T \)) is shown in Figure 19 which is calculated by the eqn [13] for machining the microelectrode with diameter of 20, 40, 60, and 80 \( \mu \)m, respectively. As shown in Figure 19, when the distance \( S_T \) is equal to 120 \( \mu \)m, increments in diameters of four microelectrodes are from 10.72 to 10.96 \( \mu \)m while comparing with \( S_T = 0 \), and in fact the difference of the increments is only 0.24 \( \mu \)m (10.96 – 10.72 \( \mu \)m). In fact, the slopes of these four curves almost remain the same. Therefore, four conclusions can be drawn as follows: (1) without considering the machined microelectrode diameter, the removed diameter \( \Delta d \) of the microelectrode can be determined only if the distance \( \Delta S \) is previously given (Figure 18(c)). (2) The distance \( \Delta d \) is much smaller than the tangential-feed distance \( \Delta S \) and the removal resolution is significantly improved. (3) It is evident from Figure 19 that, the slopes of the curves are gradually decreasing with the reduction in the distance \( S_T \) and the removal resolution is higher when the microelectrode is more closer to the symmetric axis of the machine wire guide. (4) It can be seen from the Figure 18(a) that the error effect of the horizontal alignment with respect to the wire guide orientation on the removal resolution can be ignored. For instance, if the experimental error is controlled < 5 \( \mu \)m, this could result in the error of microelectrode diameter being smaller than 0.04 \( \mu \)m.99

From the analysis mentioned above, it is possible to machine the microelectrode diameter precisely by using the high resolution of TF-WEDG and on-line measurement of the microelectrode diameters. At the position \( S_T \) of the micro-machining process as shown in Figure 19, the required diameter can be machined by feeding the value of \( \Delta S \) which is calculated by the eqn [13] after the diameter feedback of on-line measurement.99

The TF-WEDG method is performed into three steps as presented Figure 20 in order to earn high-accuracy rate. \( S_T \) works as a variable value representing the distance between the microelectrode and the wire-guide axis OO’. \( S_T > S_1 \) in the first step, therefore the axial error of the microelectrode is totally omitted by feeding a large pulse energy. At position A, the microelectrode’s diameter is measured by the on-line measurement device and feed based on second step and its diameter is determined by the eqn [13]. \( S_1 > S_T > S_2 \) according to the second step (transition step), the microelectrode feeds from the position A to the position B and the calculated diameter is achieved by machining at this position. Then, its diameter is measured again to calculate the feed amount of the final step. \( S_T = S_3 \) is the final step to feed the microelectrode from the position B to the position C, and hence the desired microelectrode is finally fabricated. The final step is a trimming process to obtain a precise diameter and surface. In the second and third steps, the negative polarity machining (the microelectrode with negative polarity) is used for higher material removal and better surface roughness. The microelectrode fabrication will follow this three steps procedure.99

In TF-WEDG method, the negative polarity machining increases the material removal from the microelectrode and decreases the surface roughness of the microelectrode. Therefore, it results in an obvious improvement of the surface quality of microelectrode as shown in Figure 21. The experimental investigation on the microelectrodes of \( \Phi 27 \) and \( \Phi 64 \) \( \mu \)m are presented in Figures 22 and 23, respectively. In the axial direction, the consistency accuracy for one microelectrode is less than 1 \( \mu \)m, and the repeating machining accuracy

![Figure 19](image1.png) Error analysis of TF-WEDG.99

![Figure 20](image2.png) Three steps of TF-WEDG method.99
for several microelectrodes is less than 2 μm. The key factors that affect this repeating machining accuracy are the unit stability of WEDG, the geometric errors in the X-axis of horizontal straightness with respect to the linear positioning, and the error in the wire diameter.

1.10.4.3.1.3 Twin-wire EDM system

The WEDG technology invented by professor Masuzawa is used to fabricate the microelectrodes. This technology employs an RC pulse generator, which can maintain high accuracy throughout the whole machining process. However, WEDG method needs a lot of time to produce the microelectrodes because of using roughing and finishing steps. On the contrary, a twin-wire EDM system, which includes combined TrC and RC two pulse generators, can be used more efficiently to fabricate microelectrode as shown in Figure 24. This system offers only one step to fabricate the microelectrodes.

The twin-wire EDM system works on two isolated wires which move on two v-shaped guides, as shown in Figure 24. In this system, two precisely machined copper wire electrodes create two separated pulse generators in one machine. The upper wire is connected a transistor pulse generator which is used for roughing step and another wire is connected an RC pulse generator which is used for finishing step. The transistor type pulse generators equipped with an additional large capacitor provides enough amount of spark energy (discharge energy) to obtain large MRR for roughing step. On the contrary, the RC pulse generator includes a smaller capacitor having reduced stray capacitance to achieve a very low amount

![Figure 21] Roughness contrast of positive and negative polarity machining.

![Figure 22] Experimental results of microelectrodes after finishing process (Ф27 μm): (a) image of microelectrodes and (b) diameter deviation.

![Figure 23] Experimental results of microelectrodes after finishing process (Ф64 μm): (a) image of microelectrodes and (b) diameter deviation.

![Figure 24] Twin-wire EDM system for the microelectrode fabrication.
of spark energy for finishing step. The lower stray capacitance and small amount of spark energy of an RC pulse generator have made it an essential discharge circuit for machining microelectrodes.\(^{100}\) By using WEDG technology equipped with an RC pulse generator, it is possible to fabricate microelectrodes with diameters as small as 5 μm.\(^{100,101}\)

As shown in Figure 24, the rod tool spindle at first feeds to the upper wire to shape the microelectrode roughly using a TrC (transistor electro-discharge circuit) electro pulse generator. When the feeding length crosses the gap between those two electrode wires, the twin-wire EDM machining system immediately starts the finish machining through the RC electro pulse generator simultaneously. Conventional EDM machining system that employs transistor type pulse generators required the pulse-ON time, pulse-OFF time, and a duty factor to achieve a high-precision machining. However, the finishing side of the twin-wire EDM machining system determines the accuracy of the microelectrodes without taking the transistor pulse generator into account. This system can produce the straight and thin microelectrodes by using high-precise position control. Fundamentally, twin-wire EDM system can fabricate the precision microelectrodes with various materials.\(^{100}\)

1.10.4.3.1.4 Fabrication of microelectrode for batch production by WEDM

The micro-WEDM machine was used to manufacture the microelectrode array with high aspect ratio. The microelectrode is clamped on the spindle machine and gradually fed in downward direction against the wire which is moving toward horizontal direction. By this process, raw material of microelectrode (a small metal rod) can be machined to a microstructure array with micro-squared pillars. For producing mass micro-holes, an array of microelectrodes is needed to cut by performing the micro-WEDM process first. Figure 25 shows the relative wire movement at some stages during the manufacturing. As shown in Figure 25(a), the wire moves at an extremely slow speed from \(-X\) to \(+X\), while the microelectrode (workpiece) is also moving in downward direction. When all of the layers are machined completely, the workpiece is separated from the wire in the \(+Z\) axis direction and then rotated around the \(Z\) axis at 90° angle for fabricating the other side as shown in Figure 25(b). After that the fabricated microelectrode array is unclamped from the machine and is mounted directly above the stainless steel plate and then moved slowly toward the downward direction for producing the mass micro-holes array as shown in Figure 25(c). Eventually, the mass micro-holes are machined by using the batch micro-EDM process (Figure 25(d)). Finally, the microelectrodes array gets shorter in length than the original one because of the consumption toward the longitudinal microelectrode direction.\(^{102}\)

Figure 26 illustrates the machined microelectrodes array and also a single microelectrode in microphotograph with the total machining time of 130 and 33 min. These microelectrodes are all uniform and consistent on the tip and the middle. The heights of all the pillars are greater than 700 μm, hence providing a enough amount of compensation in the batch micro-EDM method. Figure 27(a) illustrates the results for a single hole as well as a hole array machining. As the fabricated microelectrodes array is not unclamped and re-clamped, exceedingly excellent the micro-holes position are attained. Figure 27(b) illustrates the regular size of the partial hole.\(^{102}\)

1.10.4.3.1.5 Compliant microelectrode arrays were fabricated by WEDM

The bending stiffness of the microelectrodes can be reduced by employing wire EDM process. This process has the ability to create real 2D geometries by selectively removing desired material in points that affect the lateral yielding. Flexure, tapered, and spring-like microelectrodes were designed using Pro/MECHANICA (finite element methods) to analyze their various features as shown in Figure 28.\(^{103}\)

![Figure 25](image1)

**Figure 25** Batch production mode of mass micro-holes.\(^{102}\)

![Figure 26](image2)

**Figure 26** SEM microphotograph of the fabricated single electrode and electrode array.\(^{102}\)
A tapered microelectrode column with 0.1 mm tip reduces the bending stiffness by 5 times compared to the straight microelectrode as shown in Figures 28(a) and 28(b). On contrast, flexure feature microelectrodes with circular reliefs having a 0.05 mm depth in each 0.25 mm (Figures 28(c) and 28(d)), are more compliant than the contemporary straight microelectrode by a factor of 4. Besides, lateral rigidity of a straight microelectrode can also be reduced by creating curvatures on it. For instance, the torsional spring-type microelectrode shapes as shown in Figures 28(f) and 28(g) lowers the stiffness by roughly 15%. Microelectrode arrays of 144 microelectrodes were fabricated into single-crystal silicon blocks with 6 x 6 x 10 mm size. The pitch between two microelectrodes was maintained at 400 μm with a 5 mm microelectrode length. The contemporary straight microelectrodes, shown in Figure 29 possess a 255 x 255 μm uniform cross section of and a cut achievable in three steps. A roughing step of cutting was accomplished in germanium first with a capacitance and voltage of 9.9 nF and 150 V respectively. This profiling cut made the outlines of the microelectrodes, roughly leaving 10 µm of material on all surfaces. These extended ridges were then retraced with a
capacitance and voltage 3.3 nF of and 150 V respectively. At the next step, the workpiece was rotated at 90° angle. For the other face, the rough cut was eliminated and the finish cut was employed instead. Around 8 h was needed for machining of the entire array.  

Similar machining processes were adopted for the microelectrode arrays illustrated in Figure 30, that show the μ-WEDM capability to properly trace the complex shapes found in Figure 28. The tapered-shaped microelectrode which is depicted in Figure 30(a) has a 95 × 94 μm tip dimension. On contrast, the flexure type microelectrode arrays in Figures 30(b) and 30(c) are machined on square columns with a 250 × 250 μm cross section. The wavy microelectrode illustrated in Figure 30(d) as well as the microelectrodes with the base springs as shown in Figures 30(e) and 30(f) are based on a 220 × 220 μm cross section for creating larger curvatures.  

The μ-WEDM method and subsequent etching were performed to manufacture an microelectrode array which has 144 microelectrodes with 5 mm length. To increase the lateral compliance, the microelectrodes were tapered and machined with a bidirectional spring at the base. After performing the μ-WEDM, the microelectrode array was etched for 1 min in HNO$_3$:CH$_3$COOH:HF followed by another 1 min etching in HNO$_3$:HF. Figure 31(a) shows a SEM image of the microelectrode array and Figure 31(b) is a magnified image of the base geometry having a cross section of 100 μm. The two-directional curvatures of the base geometry act as torsional springs. Figure 31(c) shows an microelectrode tip that was etched to a very sharp point.  

Using μ-WEDM also allows variable the microelectrode lengths to a certain degree. Figure 32 shows the microelectrode array was manufactured by first machining a v-groove into one side and cutting two chamfers in the other side. This resulted in an array whose tapered microelectrode lengths were from 5 to 9 mm.  

1.10.4.3.1.6 Fabrication of series-pattern micro-disk electrode  
Schematic diagram of the essential parts of the micro-EDM working system are shown in Figure 33. A micro-EDM working system is composed of WEDG method and RC discharge circuit which are mounted on the XYZ stages with a nanometer range positioning accuracy. The stage accuracy this method is
illustrated in Table 7. In the WEDG process, the tool electrode is basically a wire electrode which travels on a wire guide. By adjusting the discharge voltage and the capacitance at the improving RC discharge circuit, a moderate energy discharge can be obtained to make a micro-component. This method is a free-contact force machining process with a small sparking gap between electrodes.

In the configuration of the micro-EDM working system, a main mandrel shaft is horizontally set on the bearing surface, which is known as horizontal micro-EDM working system. A raw pin can be clamped at the mandrel shaft by a capillary and a ceramic alignment sleeve. The raw pin can be horizontally rotated with the main shaft by means of a transmission motor. As illustrated in Figure 34, the machining can be performed through the sparking discharge between the pin and the wire traveling on the WEDG. The debris is effectively removed from the gap during the machining by gravitational force due to the horizontal position of the pin. U500 controller can control the relative position between the wire electrode and raw pin as shown in Figure 33.

Table 7 Stage accuracy of the horizontal micro-EDM working system

<table>
<thead>
<tr>
<th>Travel range</th>
<th>XYZ: 50 × 50 × 50 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incremental motion</td>
<td>XYZ: 0.1 µm</td>
</tr>
<tr>
<td>Velocity range</td>
<td>2–0.0005 mm min⁻¹</td>
</tr>
<tr>
<td>Velocity accuracy</td>
<td>± 2% RMS</td>
</tr>
<tr>
<td>Pitch/yaw/roll</td>
<td>XYZ &lt; 20 lrad</td>
</tr>
</tbody>
</table>

The machining procedure of a single micro-disk can be extended into the fabrication of multiple micro-disks as illustrated in Figure 35. However, some factors influence the minimum interval between disks which should be specially noticed and discussed.

Firstly, based on the fabrication procedures outlined, a raw pin can be fabricated into the tool electrode with the
micro-disk by the micro-EDM system illustrated in Figure 33. This tool electrode is rotated with the horizontal rotation on the main shaft by the means of a transmission motor, such tool electrode is called as micro-rotating disk electrode (MRDE).104

A polished work-piece plate is placed vertically on the XY table. Before the machining is performed, the positioning detection circuit is employed precisely to detect first position. Moreover, the positioning detection circuit maintains the relative original position between the work-piece surface and outermost MRDE. The MRDE can then be fed into the work-piece from the surface until it reaches the desired depth. A straight line with a micro-slit can thus be formed by means of moving the Y-stage which is carrying the work-piece, as schematically presented in Figure 36.104

### 1.10.4.3.2 Rotating sacrificial disk

Figure 37 illustrates the microelectrode fabrication process using a rotating sacrificial electrode. Electrical discharges have caused the erosion on the rotating electrode during the fabrication process. However, the erosion is almost uniformly distributed over the whole electrode perimeter during micro-EDM. The dimensional change of the rotating electrode is almost negligible in microelectrode fabrication by considering the diameter difference between the sacrificial electrode and microelectrode. Moreover, the rotating electrode with 0.5 mm thick provides the same effect as stationary electrode on the surface finish, since its wideness is sufficient to produce a smooth surface, as can be seen in Figure 38.5

### 1.10.4.3.3 Stationary BEDG

Stationary BEDG is the simplest ways to fabricate a micro-electrode. Figure 39 illustrates the fabricated micro-electrode using BEDG process. This method can produce the micro-electrode with smooth surface. However, some taper is usually seen in the microelectrode shape and the accuracy is not as good as desired because of the wear occurs on block electrode...
as shown in Figure 40. Since the microelectrode feeds upward and downward during microelectrode fabrication, the lower (tip) portion has a greater chance to face the block electrode, and consequently is subjected to more discharges during the machining. Also, slight tilting of the block electrode toward the microelectrode does not shape to improve the tapered shape. Figures 40 and 41 show tapered and uneven diameter of microelectrode respectively. The block electrode is easy to setup but shape and dimensions of the microelectrode are not easy to control.\footnote{Figure 38: Fabricated microelectrode using rotating disk.}

### 1.10.4.3.4 MBEDG

Figure 42 shows the moving BEDG (MBEDG) which is combined the advantage of the rotating sacrificial disk and BEDG methods. Block electrode needs a very simple setup and the surface of the machined microelectrode is generally smooth. However, the precision of shape is not as improved as desired, and the microelectrode generally possesses a tapered shape as a result of the wear in the block electrode. In this fabrication process, the microelectrode in the Z axis controlled the EDM gap by the top surface of the block electrode. A relative feed between the microelectrode and the block electrode was employed longitudinally with the block electrode. During the Moving BEDG method, erosion occurred on the moving block electrode by the electrical discharges. However, the erosion occurred almost in a uniform manner over a very larger area of the block electrode. In addition, most of the sparks occurred between the un-machined part of the microelectrode and the top surface of the block electrode. Almost no spark occurs at the side surface of the microelectrode. This produced the not tapered microelectrode with very smooth surface and good accuracy in shape. However, there was difference in the produced microelectrode length which is smaller than the desired length always because of the created groove on the block electrode surface. The difference between the actual length and the desired length of the microelectrodes is almost negligible by considering the machined area between the microelectrode and block electrode.\footnote{Figure 40: Tapered microelectrode is produced using BEDG.}

Figure 43(a) illustrates the CuW microelectrode with about 50 μm diameter and 3 mm length (aspect ratio = 60) was fabricated using BEDG. Figure 43(b) shows the improvement in taperness of the microelectrode which was produced using moving BEDG. Figures 44(a) and 44(b) illustrate the W microelectrodes which were fabricated using BEDG and moving BEDG methods respectively. It is clear that the moving

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\footnote{Figure 39: BEDG.}

\footnote{Figure 41: The microelectrode uneven diameter is machined using BEDG.}

\footnote{Figure 43(a): CuW microelectrode with about 50 μm diameter and 3 mm length (aspect ratio = 60) was fabricated using BEDG.}

\footnote{Figure 43(b): Improvement in taperness of the microelectrode produced using moving BEDG.}

\footnote{Figure 44(a): W microelectrode fabricated using BEDG.}

\footnote{Figure 44(b): W microelectrode fabricated using moving BEDG.}
BEDG method can produce less tapered microelectrodes and provides superior dimensional accuracy.  

1.10.4.3.5 Micro-turning process
The main problem that occurs during the micro-turning of the microelectrode is its deflection. Figure 45 illustrates the deflection of end portion of the microelectrode measured using a deflection sensor. Experiments revealed that the microelectrode is bending in normal (X) as well as tangential (Y) direction of the microelectrode contact region. Moreover, the microelectrode deflects toward the rake surface (top surface) of the cutting tool. It is very difficult to get straight microelectrodes below 100 μm diameter band in many cases. The microelectrode either gets broken or starts to wobble due to the excessive cutting force in radial direction on this microelectrode. Figure 46 demonstrates one of this kind of microelectrode which is machined by the conventional micro-turning process.

Figure 47 shows the polycrystalline diamond (PCD) inserts with 100 μm tool nose radius (designed for finishing step or
light cutting) was used for micro-Turning. This tool nose divides the cutting force on the microelectrode into two different force components, $F_x$ and $F_y$ as shown in Figure 48(a). Basically, the $F_y$ cutting force component performs the actual cutting whereas the $F_x$ component is responsible for the microelectrode deflection. Figure 48(b) illustrates the actual cutting with the commercially available PCD inserts under a tool scope.

Figure 44 W microelectrode, (a) with 60 μm diameter and 3 mm length (aspect ratio = 50) was produced by the BEDG method, (b) with 40 μm diameter and 3 mm length (aspect ratio = 75) was produced by the moving BEDG method.

Figure 45 Microelectrode deflection during micro-turning.

Figure 46 A 100 μm diameter microelectrode was machined by conventional micro-turning.

Figure 47 The tool geometry of commercially available PCD inserts for finishing step (light cutting).

1.10.4.3.6 EDM of micro-rods by self-drilled holes

Figure 49 presents the working principle of the developed micro-EDM process. In this process, a rod electrode is rotated with negative polarity and fed into a plate electrode to create a hole. When the rod electrode is returned to its initial place, the axis gets off-centered from the hole center at a certain distance.
For instance, some holes are fabricated on a metal plate to depict examples of multiple cutting forces and actual cutting with the commercially available PCD inserts under a tool scope.

Figure 52 shows the principle of obtaining micro-rods by self-drilled holes.

Then, the rod electrode polarity is reversed and the rod electrode is fed into the plate electrode either stationary or with rotation. The straight rod electrode (microelectrode) can be achieved if the wear does not occur at the outlet holes even though the inlet holes have already worn out. If the machining gaps between the hole and the electrode are determined before as illustrated in Figure 50, the rod electrode with any diameter can be fabricated. With traditional methods, it is essential to measure the machined rod electrode diameter and rectify the starting point of machining from the previous measured results. The benefits of this new process include no adjustment of the starting point is needed and accurate machining efficiency.

Unlike reverse-EDM and WEDG, this process can produce the reference holes with the rod electrode, therefore no reference positioning of the tool electrode to the workpiece is needed. As a result, operation becomes easy and shorter. In addition, stable EDM is achieved because of the wide electrical discharge area compared with WEDG, and complicated shapes can be formed.

Figure 51 shows the fabricated micro-electrodes after various machining conditions. Figure 52 illustrates micro-electrodes fabricated by double forming is still taper. Figure 53 demonstrates the micro-electrodes were fabricated by various holes for forming and holes obtained by EDM using these tools.

1.10.4.3.7 Reverse EDM

In micro-EDM, micro-holes, and micro-structures are fabricated by feeding a micro-electrode machined by wire EDM or grinding process as illustrated in Figure 54(a). Micro-EDM can be used for fabrication of the micro-holes and micro-electrodes. For instance, some holes are fabricated on a metal plate by using EDM. After applying a positive voltage to a workpiece material for machining micro-electrodes, the workpiece is fed down to the holes of the metal plate while being machined by EDM. However, the areas around the holes are not machined and remain, getting into a micro-electrode at each hole as illustrated in Figure 54(b). This machining process is generally called reverse EDM (REDM). Different micro-electrodes shapes can be machined by REDM, which is difficult to fabricate using normal EDM.

Figure 55 depicts examples of multiple micro-electrodes and U-shape micro-electrode which were fabricated by REDM.

1.10.4.3.8 Hybrid process

1.10.4.3.8.1 Micro-turning-micro-EDM hybrid machining process

As has been described before, all of the micro-electrode fabrication processes have their own benefits and disadvantages. The disadvantage of the conventional micro-turning is the transferring the micro-electrode to EDM machine. Moreover, rotating sacrificial disk, WEDG, BEDG, moving BEDG, and self-drilled holes are very difficult for automation and are always prone to error. In most cases, the operator is required to check the whole fabrication process and perform manual compensation to find the error. Besides, it takes more than few hours for the electrode fabrication process. For example, it takes about 3–4 h to fabricate a micro-electrode with 15 μm diameter and 0.5 mm length using a commercially available 500 μm diameter tungsten electrode with by moving BEDG method. It is a well-known fact that tungsten electrode has negligible wear against stainless steel and 100 holes could be machined on 50 μm thick SUS-304 plate with this micro-electrode. A new hybrid machining method for micro-turning can be employed to machine very fine micro-electrodes and nearly eliminates all the disadvantages of micro-electrode fabrication methods which used micro-EDM machine.

Figure 56 shows the process of turning-EDM hybrid machining. In this type of machining process, EDM is carried by using a micro-electrode. Therefore, an electrode of certain length is machined using the micro-turning process. Elimination of clamping error and minimizing the electrode deflection is possible in hybrid machining process, which results in the significant improvement in machining accuracy. When variable diameters of micro-electrode are required, turning can significantly save the micro-electrode preparation time as compared to the EDM processes. Non-rotational cylindrical micro-components such as key slot or flat bar can also be fabricated using hybrid machining technology with the help of EDM process followed by turning.
As described before, it is always very difficult by micro-turning to achieve straight microelectrode below 100 μm diameter and in a lot of cases, the microelectrode is either broken or starts to wobble due to excessive radial cutting force on this microelectrode. A commercially available PCD insert can be modified to achieve a very sharp cutting edge which would reduce the $F_x$ component of cutting force significantly (Figure 57) and thus this makes it possible to achieve straight microelectrode with much smaller diameter. An approach has been developed to manufacture an ultrasharp-edged tool from the commercially available PCD insert using micro-EDM. A rotating electrode is mounted on the spindle and used to perform micro-EDM (EDG) on the PCD tool edge to produce a very sharp edge. This is illustrated in Figure 58. Table 8 shows the parameters that were used during the tool tip fabrication. Figure 59 shows the
commercially available PCD insert (a) and the modified PCD tool (b). The modified PCD tool has less than 5 mm tool nose radius.

In Figure 60, a microelectrode and the EDG-edged tool used for machining the microelectrode under a tool scope is observed. This has stretched the possibility of micro-turning to an extreme. This method illustrates much improvement on the machining time compared to rotating sacrificial disk, WEDG, BEDG, moving BEDG, and self-drilled holes which takes few hours to fabricate as mentioned earlier. In addition, this method does not require much operator intervention and can mostly be automated due to the less chances of error. Two millimeter long microelectrodes with less than 20 μm diameter have been fabricated very easily. The fabrication process for a 2.0 mm long microelectrode takes less than 10 min. Figure 61(a) shows a microelectrode with 22 μm diameter was produced by micro-turning process and after drilling about 10 holes on 100 μm thick SUS-304 plate. Figure 61(b) demonstrates a graphite microelectrode of 0.5 mm long and 19 μm in diameter that is similarly produced.

1.10.4.3.8.2 Self-drilled holes–TF-WEDG hybrid machining process

Figure 62 shows the hybrid process of self-drilled holes and TF-WEDG holes for the complementary benefits of high efficiency and accuracy. First, the tool electrode with negative polarity drills holes on the plate electrode. Then tool electrode is returned to its initial position and the axis gets off-centered from the hole center at a certain distance. Next, tool electrode polarity changes to the positive and is fed into the plate electrode with rotation in order to machine the microelectrode (rod electrode). The microelectrode is fabricated with dimension close to the desired diameter in the rough machining condition. Finally, TF-WEDG method with the on-line measurement is used to fabricate the accurate microelectrode. A charge coupled device (CCD) is utilized for the on-line measurement.

![Figure 52](image1.png)  
**Figure 52** Image of microelectrodes obtained by double forming (110 V, 100 pF, 2 μm s⁻¹, and 5 min): (a) first time (78 μm) and (b) second time (84 μm).

![Figure 53](image2.png)  
**Figure 53** Image of microelectrodes were fabricated by various holes for forming and holes obtained by cross-shaped section (110 V, 100 pF, and 2 μm s⁻¹).

![Figure 54](image3.png)  
**Figure 54** (a) Normal EDM and (b) REDM (reverse EDM).
Continuous machining process of array micro-holes

To gain high consistency accuracy of array micro-holes and to avoid the negative effects of low rigidity of long microelectrode, a continuous machining process is presented according to the TF-WEDG method. Figure 63 demonstrates the continuous machining process of array micro-holes. After the implementation of the self-drilled holes process (Figure 62), the microelectrode is machined with a larger diameter $D$ and an
effective length $L$. The diameter $D$ guarantees the rigidity of the electrode with the length $L$. As shown in Figure 63(a), firstly the microelectrode with the desired diameter $d$ and proper aspect ratio of length $L_1$ is machined by TF-WEDG. The aspect ratio guarantees enough rigidity of the microelectrode. The desired aspect ratio between $d$ and $L_1$ guarantees enough rigidity of the microelectrode. Secondly, the microelectrode is utilized for micro-hole EDM drilling (Figure 63(b)). The microelectrode becomes shorter (wear length $\Delta L$) after micro-EDM drilling the expected number of holes because of electrode wear during micro-EDM. When the microelectrode becomes too short after micro-hole EDM drilling (Figure 63(c)). The remained part of the microelectrode with diameter $D$ is re-machined by TF-WEDG to produce again the microelectrode with diameter $d$ and length $L_1$. The procedures are repeated (Figures 63(a)–63(c)) are repeatedly performed until all designed holes are produced (Figure 63(d)). Array micro-holes can be produced by the circulation process.

Based on the continuous machining process, $5 \times 5$ array micro-holes were produced through 5 times microelectrodes machining by TF-WEDG and 5 times micro-hole machining with 5 micro-holes each time. The consistency accuracy of micro-holes is evaluated by measuring the magnified images of 25 micro-holes. The experimental results of the micro-holes and the used microelectrodes are presented in Figures 64(a) and 64(b) respectively. The results revealed that the consistency accuracy of 25 micro-holes of $\Phi 73 \ \mu m$ is $\pm 1.1 \ \mu m$, and the drilling time of single micro-hole is 1 min 10 s on the 200 $\mu m$ thick stainless steel plate.

1.10.4.3.8.4 LIGA–micro-EDM hybrid machining process

The flow of the LIGA process is shown in Figure 65. The LIGA process (step 1–5) which was developed by the University of Wisconsin at Madison fabricates the electroplated electrodes for the micro-EDM. The electrodes that are produced on a silicon substrate are basically negative-type microstructures with ultrafine designs. An electroplated metal plate is used to form many microelectrodes. In the step 5, the metal plate that has the electrodes is released from the substrate as step 5 as the negative-type electrodes are self-supporting. The electrode position in the metal plate is very accurate as photolithographic methods are used for electrode fabrication.

Step 6 shows a positive type of patterned structure is fabricated by feeding the WC–Co workpiece into one of the electrodes using micro-EDM. During this step the shape of the electrode is deformed due its wear. To achieve a uniform cross section along the workpiece length, the electrode has to be replaced before its deformation takes place throughout the thickness. Such deformed electrodes can be replaced with a new electrode by X-Y position between the workpiece and each of the electrodes. This can be done with a high precision as the accurate position of the electrodes as in the step 7. A patterned microstructure with high aspect ratio is achieved after repeating the machining and replacing process.

In the LIGA method an array of nickel electrodes with a negative type gear pattern with 200 $\mu m$ outside diameter was machined as illustrated in Figure 66. The height of the structure is 300 $\mu m$. The primary shape of the nickel electrode is illustrated on the left side of Figure 67. It is deformed by metal wear as illustrated on the right side of Figure 67. Deformation occurs when the WC–Co workpiece with 300 $\mu m$ diameter is fed to the electrode about 400 $\mu m$ by using micro-EDM. Though the length of the EDMed structure is confined to the amount of feed depth in single machining, much larger height can be fabricated be repeating the machining and replacing the worn electrode with a new one at X-Y position.

Figure 68 illustrates a positive-type WC–Co microstructure having a 1 mm length fabricated by using three different electrodes of the serial micro-EDM. However, much higher aspect ratio
Figure 61  (a) A 22 μm brass electrode fabricated by micro-turning process and used for machining 10 micro-holes on 100 μm thick stainless steel plate, showing some wear.\textsuperscript{3,4}  (b) A 19 μm graphite micro-microelectrode of 0.5 mm length fabricated by micro-turning process.\textsuperscript{5}

Figure 62  Schematic diagram of hybrid machining process (self-drilled holes and TF-WEDG).\textsuperscript{99}

Figure 63  Continuous process for array micro-holes.\textsuperscript{99}

Figure 64  (a) Experimental result of array micro-holes. (b) Microelectrode after machining micro-holes.\textsuperscript{99}
structure with over 1 mm length can be fabricated by increasing the replacement cycles. The variation in the outside diameter of the 1 mm long structure along its length is measured and the result is illustrated in Figure 69. The provided graph depicts this particular gear length varies by an amount of about 4 μm in the outside diameter along its length. The results illustrate this process has capability to produce high aspect ratio microstructures from various bulk materials as well as WC–Co.

1.10.5 Prospective on Process Selection

A micro-mold cavity is needed, when the mass production of various micro-components is involved. Micro-holes are required in micro-dies and micro-molds. Moreover, hard materials are used for micro-injection-mold, which requires very accurate machining of complex and three dimensional shapes in micron range.

Tungsten carbide (WC) and composite of tungsten carbide (WC–Co) are employed for producing cutting tools, dies, other special tools and components owing to high hardness, strength, wear and corrosion resistance of WC and WC-Co over a wide range of temperatures; therefore, machining of WC plays a
remarkable roles in recent trend of manufacturing. EDM and electro-chemical machining (ECM) are the only feasible processes for the modern machining of WC–Co. Investigation of Watson and Freer revealed that due to a resistant oxide layer generation on the surface, MRR is very slow during ECM of WC–Co. In fact, more the percentage of cobalt in the alloy increases, the amount of MRR decreases more with it. Singh reported that, the EDM machining process is more suitable for the machining of carbides and other refractory materials.

In the EDM process, conductive materials are removed according to the thermal energy (melting and partial vaporization of the workpiece) produced by series of sparks occurring between the electrode and electrical workpiece. EDM is a useful process in industry for machining conductive materials with accurate dimensions regardless of hardness, strength, and toughness. Adding aluminum powder to the dielectric leads to increased MRR and improved surface roughness during EDM. The chain formation among powder particles in the dielectric helps bridge the gap between electrode and workpiece that can cause an early explosion. Therefore, faster sparking within discharge and faster erosion of the workpiece surface take place. Micro-EDM and EDM have the same characteristics, with the only differences being the electrode size, discharge energy, and axis movement resolution at the micron level in micro-EDM. Micro-mold making, production of dies and cavities, and producing of the complex three-dimensional shapes at the micro-level are the major functions of micro-EDM. In EDM and micro-EDM, no direct contact and negligible force between the workpiece and tool cause the elimination of tool deformation, chatter, mechanical stress, and vibration errors during machining. Therefore, micro-EDM is one of the most effective methods of machining of ECM (WC).

Jahan et al. used AgW, CuW, and W microelectrodes for machining of WC–10wt.%Co. The highest MRR was obtained with the CuW electrode. Also, Jameson stated that "copper tungsten is often used for machining of tungsten carbide." Electrode polarity produces a re-sticky effect during EDM of tungsten carbide. It was reported that the WC workpiece surface does not have any re-sticky regions after finishing with positive electrode polarity in the EDM process. On the other hand, negative electrode polarity for micro-EDM of WC is more suitable as it provides higher MRR, lower electrode wear, better surface roughness and controlled performance. Jahan et al. investigated the micro-EDM parameters effects on WC (micro-hole quality) using a transistor and RC-type pulse generator. The results indicated that micro-EDM performance relies on the discharge energy. It has been reported that controlling the performance of RC-type micro-EDM is easier as the electrical discharge energy is determined by voltage and capacitance (capacitor) as parameters during micro-EDM of WC–10%Co and 0.6% others. Moreover, in transistor-type micro-EDM, they applied voltage, resistance, pulse-ON time, pulse-OFF time, and electrode rotational speed as parameters during micro-EDM of WC–10%Co and 0.6% others.

The thermal stress during EDM of tungsten carbide creates micro-cracks on the machined surface, as tungsten carbide has low thermal conductivity and brittleness. This is especially true during EDM of WC–Co composite, since WC and Co are two quite different phases. Micro-cracks and micro-pores on the machined surface severely deteriorate the service life, reliability, and machining precision of tungsten carbide tool or mold. Suitable machining parameters during EDM of WC reduce the damage caused by the micro-cracks on the machined surface. It has also been reported that the EDM process has no effect on the microstructure of the bulk workpiece material (WC). This means that EDM causes damage only on the machined surface (surface layer) within a certain depth. Hence, a complimentary finishing operation might become necessary to remove micro-cracks on the machined surface and to produce good surface quality when utilizing the EDM process. On the other hand, the depth of the damaged layer and the average length, width, and number of micro-cracks reportedly increase with increasing current and pulse-ON time. The micro-cracks are more visible when the spark energy (electrical discharge energy) is set to a higher level. Moreover, the machined surface becomes smoother as the spark energy is set at a lower level.

Moreover, micro-EDM possess a significant place in the field of micromachining. Because of its non-contact nature, a very long and thin electrodes can be used in micro-EDM. Main disadvantages of micro-EDM are EWR and low MRR. Electrode wear can be balanced by changing the microelectrode, preparing a longer microelectrode from the earlier stage or by utilizing the microelectrode in situ for further machining. Also, changing the microelectrode during machining causes decreased accuracy due to changing the setup or microelectrode re-clamping. Thus, An on-machine microelectrode fabrication can eliminate clamping error in the micro-EDM process.

The microelectrode production procedures explained have a number of benefits. For one, the BEDG method setup is simple and the rotating sacrificial disk can be used to fabricate microelectrodes with smooth surface. The block electrode can fabricate cylindrical, triangular, or square microelectrodes at low cost. Moreover, the moving BEDG process has all the advantages of the rotating sacrificial disk and BEDG method. Therefore, moving BEDG can be utilized to manufacture non-tapered cylindrical or non-cylindrical microelectrodes with smooth surface and accurate shapes at low cost using a simple setup.

![Figure 70](image-url) Online measurement (a) Laser light and (b) charge coupled device.
 Nonetheless, the microelectrode fabrication procedures addressed have some disadvantages as well. For instance, deflection occurs during thin microelectrode fabrication with the micro-turning process.\(^4\) Also, the microelectrode produced with a micro-turning machine needs to be transferred and clamped to the micro-EDM or EDM machine. The fabricated microelectrode cannot be aligned on the micro-EDM or EDM machine, which causes reduced accuracy. The self-drilling hole method usually produces tapered microelectrodes.\(^5\) In addition, tapered or uneven microelectrode diameters are produced with the BEDG process.\(^6\) The rotating sacrificial disk method produces microelectrodes with better surface roughness than the WEDG (guided running wire) process.\(^7\) Moreover, WEDG requires special equipment and high investment. Rotating sacrificial disk setup is relatively complicated. Hybrid machining requires special equipment and high investment. It can be easily outsourced through other workshop. Using a rotating sacrificial disk involves a rather complex setup.\(^8\) Hybrid machining requires special equipment and high investment. Besides, it cannot be easily obtained from all workshops.

Moreover, on-machine measurement is needed to achieve the desired and accurate microelectrode because of estimation of the microelectrode diameter is very difficult. Thus, optical measurement and CCD were applied for the microelectrode measurements, as shown in Figure 70.\(^3, 5, 9\)

In this research, EDM machine is used instead of micro-EDM and hybrid machines, because the EDM machine is cheaper and more widely available in workshops. CuW is selected as microelectrode to produce the micro-holes in WC–16%Co. There is less information about the effects of micro-EDM parameters (voltage, current, pulse-ON time,
pulse-OFF time, rotating speed, and capacitor) on micro-EDM drilling of WC–16%Co using an ordinary EDM machine. This research is carried out to investigate the effects of micro-EDM parameters on MRR, EWR, surface roughness, micro-cracks, migration of material to the workpiece, and overcut during micro-EDM drilling of WC–Co using an EDM machine.

1.10.6 Methodology

1.10.6.1 Experimental Setup

In this research, an AG40L Sodick electrical discharge machine was used to replace the micro-EDM machine, as shown in Figure 71. This EDM machine has 0.0001 mm (0.1 μm) movement resolution on each axis and the amount of discharge energy can be controlled toward lower energy. Figure 72 shows the experimental setup for fabricating microelectrodes and measuring microelectrodes diameter, electrode wear, and micro-holes EDM drilling. CuW material (30%Cu + 70%W) with 1 mm diameter was selected as the raw material for the microelectrode and WC–16%Co (HS-US16 plate with 0.331 mm thickness) was chosen as the workpiece. Tables 9 and 10 illustrate the properties of the CuW electrode and WC–16%Co. The copper block electrode was used to manufacture the microelectrodes as shown in Figure 72. A WC electrode was utilized to dress the tapered microelectrode after micro-holes EDM drilling in order to produce a straight electrode. The polarity of the microelectrode during fabrication and electrode dressing was positive, while negative polarity

<table>
<thead>
<tr>
<th>Table 9</th>
<th>Table properties of CuW microelectrode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kind</td>
<td>Ingredient</td>
</tr>
<tr>
<td>CuW</td>
<td>30Cu + 70 W</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 10</th>
<th>Properties of WC–Co (typical nominal properties)</th>
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</thead>
<tbody>
<tr>
<td>Grade</td>
<td>Cobalt</td>
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<tr>
<td>HC-US16</td>
<td>13.82</td>
</tr>
</tbody>
</table>

[Figure 73] Measuring frontal wear of microelectrode (a) microelectrode before micro-hole EDM drilling touches gage block, (b) microelectrode after micro-hole EDM drilling, (c) microelectrode after micro-hole EDM drilling touches gage block, (d) 3D shape of section a, and (e) 3D shape of section c.
helped produce the micro-holes. Oil-based dielectric fluid mixed with aluminum powder (PGM WHITE 3) at 1.5 g l\(^{-1}\) was also used as it is recommended by Sodick company\(^{126}\) and the excitation of the aluminum powder in dielectric can help increase MRR and improve the surface quality during EDM.\(^{27,91}\)

A 10 mm thick gage block was used to measure the frontal wear of the microelectrode. The gage block and copper block electrode were aligned with a dial test indicator with 2 \(\mu\)m accuracy. The frontal electrode wear was measured in the steps shown in Figure 73 and eqn [14]. First, the microelectrode touches the top surface of the gage block at point \(O_1\) before micro-hole EDM drilling (Figures 73(a) and 73(d)), then it will be touch again the top surface of the gage block \(O_2\) after machining the micro-hole (Figures 73(c) and 73(e)). The difference between these positions shows frontal electrode wear (Figure 73(b)).

\[
\text{Front wear} = |O_2 - O_1| \quad [14]
\]

1.10.6.2 Micro-EDM of WC–Co

Two CuW microelectrodes with 165.2 and 169.7 \(\mu\)m diameter and around 6.8 mm initial lengths (Figure 74) were utilized for producing micro-holes. These two electrodes were fabricated on-machine by moving BEDG process as described in our previous paper\(^{127}\) and carried out according to the experimental setup shown in Figure 72. As described before, the polarity of the microelectrode during fabrication and electrode dressing was positive while negative polarity was used for producing micro-hole. Through holes were produced on WC–16%Co plate with 0.331 mm thickness. After micro-EDM drilling of every hole, the microelectrode becomes tapered. The dressing process serves to remove the taper of the microelectrode and produce a straight microelectrode for the next micro-hole EDM drilling based on Figure 75 and using setup shown in Figure 72. Voltage, current, pulse-ON time, pulse-OFF time, rotating speed, and capacitor were adopted as the
parameters to analyze MRR, EWR, surface roughness, micro-crack, migration of material to the workpiece, and overcut during micro-EDM drilling of WC–Co using EDM machine. MRR, EWR, and overcut were calculated by following eqns [8, 9, and 11], respectively (the geometry is shown in Figure 13 and Figure 73).\(^2\) Table 11 demonstrates the machining parameter levels and symbols.

The experiments were designed with \(2^6\) fractional factorial design and 3 center points consisting of 19 runs including \(16\) (= \(2^6\)) and 3 center points. These (resolution IV designs) are designs in which no main effect is aliased with any other main effect or with any two-factor interactions, but two-factor interactions are aliased with each other. The factorial effects defining contrast are \(1 = ABEF = ACDF = BCDE\). The alias relationships are as follows:

\[
\begin{align*}
A &= BEF = CDF \\
B &= AEF = CDE \\
C &= ADF = BDE \\
D &= ACF = BCD \\
E &= ABF = BCD \\
F &= ABE = ACD \\
AB &= EF \\
AC &= DF \\
AD &= CF \\
AE &= BF \\
AF &= BE = CD \\
BC &= DE \\
BD &= CE \\
ABE &= ADE = BDF = CEF \\
ABD &= ACE = BCF = DEF
\end{align*}
\]

The three-, four-, five-, and six-factor interactions are considered errors. Therefore, the aliased of two-factor interactions are important in this case.

### 1.10.7 Results and Discussions

#### 1.10.7.1 Analysis of Results on Micro-EDM of WC–Co

Table 12 shows the experimental design and results. Moreover, Figure 76 demonstrates the effects of the micro-EDM parameters on the holes' diameters and shapes. As can be seen in Figure 76, various machining parameters produced micro-holes with different diameters and shapes. The micro-hole's diameters depend on microelectrode's diameter, overcut, and electrode wear.

**Table 11** The levels of machining parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameters</th>
<th>Unit</th>
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<th>Center</th>
<th>High</th>
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<td>A</td>
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<td>Pulse-on time ((t_{on}))</td>
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<td>5</td>
</tr>
<tr>
<td>D</td>
<td>Pulse-off time ((t_{off}))</td>
<td>%</td>
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<td>5</td>
<td>9</td>
</tr>
<tr>
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<td>Rotating speed (R)</td>
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<td>Capacitor (C)</td>
<td>(\mu F)</td>
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</table>

**Table 12** Experimental design and results

<table>
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<tr>
<th>STD</th>
<th>V</th>
<th>I_p</th>
<th>(t_{on})</th>
<th>(t_{off})</th>
<th>R</th>
<th>C</th>
<th>MRR</th>
<th>EWR</th>
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<td>10</td>
<td>0.05</td>
<td>0.0423782</td>
<td>27.16618</td>
</tr>
</tbody>
</table>
In the micro-EDM process, the micro-hole is very small and low amounts of energy for material removal causes to produce small overcut. So the chips cannot be removed easily from the sparking gap (between the microelectrode and workpiece) inside the micro-hole. The remaining chips inside the micro-hole are passed on to the workpiece by the spark electricity force. The remaining chips are re-machined with spark energy into smaller than normal amounts of removed material from the workpiece material, as described in Figure 78. This leads to inefficient EDM. The smaller chips can be removed more easily. Also, the chips collected in the sparking gap create unstable servo operation, which further deteriorates machining efficiency due to the electrode-to-workpiece voltage variation with the free movement of chips. The machine's servo system advances and holds the position or retracts the electrode from the workpiece by comparing the electrode-to-workpiece voltage to a reference voltage. The electrode moves forward and reverses, increasing the chip movement on the surface.  

1.10.7.1.2 MRR and EWR

Design-Expert software was used to analyze the experimental outcomes for MRR and EWR. Analysis of variance (ANOVA) was conducted to test the significance of the models, individual
Figure 77  Amount of overcut during various machining conditions.

![Figure 77](image1)

Figure 78  Chip collection and re-machining in sparking gap.34

![Figure 78](image2)

Table 13  ANOVA table for MRR

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of squares</th>
<th>d.f.</th>
<th>Mean square</th>
<th>F-value</th>
<th>Prob &gt; F</th>
<th>Status</th>
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<td>Model</td>
<td>0.11</td>
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<td>0.016</td>
<td>152.44</td>
<td>&lt; 0.0001</td>
<td>Significant</td>
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<td>A-Voltage</td>
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<td>18.72</td>
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<td>B-Current</td>
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<td>0.011</td>
<td>101.71</td>
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<tr>
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<tr>
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<td>15.84</td>
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<td>Not significant</td>
</tr>
<tr>
<td>Cor total</td>
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<tr>
<td>R-Squared</td>
<td>0.9907</td>
<td></td>
<td>Adj R-Squared</td>
<td>0.9842</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pred R-Squared</td>
<td>0.9634</td>
<td></td>
<td>Adeq precision</td>
<td>31.929</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
model terms and lack-of-fit. Square root transformation was applied on the MRR response for ANOVA validation, while EWR did not require any transformation. Tables 13 and 14 demonstrate the ANOVA tables for MRR and EWR. If the 'Prob > F' value is less than 0.05, it is significant. In this research, A, B, C, E, F, AB, and AF were
significant model terms for MRR response. Moreover, B and F were the most significant factors. But AB, EF, AF, BE, and CD were possibly significant due to alias. The ANOVA table results for EWR response depict that B, C, D, AC, AD, and AE were significant. In addition, C was the most significant factor, while AC, DF, AD, CF, AE, and BF were possibly significant.

Insignificant lack-of-fit is desirable for MRR and EWR responses. The outcomes for both MRR and EWR illustrate that an R-Squared value approaching one is desirable. In addition, there were minor differences between Adj. R-Squared and Pred. R-Squared, meaning that the models had acceptable transaction between the input and output parameters. Furthermore, Adeq. Precision greater than four is desirable, as it measures the signal-to-noise ratio.\textsuperscript{32}

Residuals must have normal distribution and constant variance. Figure 79 depicts that a normal probability plot of residuals mapped the residuals versus the predicted response for MRR and EWR after the square root transformation was performed only on MRR. Figures 79(a) and 79(c) reveal small departures from the straight line in the normal probability plot of residuals for MRR and EWR, which are common.

**Figure 80** Response graphs for MRR vs. (a) voltage, (b) current, (c) pulse-ON time, (d) rotating speed, and (e) capacitor.
Figures 79(b) and 79(d) depict unusual scatter and patterns. Based on these plots, it can be concluded that the residuals had normal distribution and constant variance after using the square root transformation to analyze and model MRR response.

Figure 80 illustrates the response graph for MRR. According to Figure 80, MRR increased with amplifying current, rotating speed and capacitor, and decreasing voltage and pulse-ON time. The current and capacitor were the most significant factors; however, the effect of the capacitor was greater than the current. The voltage controls the discharge gap between the microelectrode and workpiece, and increasing the voltage increases the discharge gap. Suitable voltage according to current, pulse-ON time, pulse-OFF time, capacitor, and rotating speed results in improved MRR. Figure 80(a) demonstrates that the amount of MRR decreased with voltage greater than 50 V because the discharge gap was larger than the suitable range for low amounts of energy in micro-EDM (current (0.4–5 A), pulse-ON time (1–5 μs), and capacitor (0–0.1 μF) are low). Based on Figure 80(b), MRR increased with current amplification due to the rising amount of heat and energy transmitted to the workpiece for melting and vaporization. Figure 80(c) shows the effect of pulse-ON time on MRR. Sparks occurred during pulse-ON time. Increasing pulse-ON time causes an increase in the amount of energy. During long pulse-ON time, sparks initially take place between the microelectrode and workpiece, after which some of the sparks take place between the microelectrode and chip and some between the microelectrode and workpiece owing to the difficulty in removing chips between the microelectrode and workpiece. The occurring sparks between the microelectrode and chips cause the chip size to decrease. Thus, machining efficiency is reduced. Another reason for the further decrease in machining efficiency is that chips collected inside the micro-hole produced unstable servo operation. As a result, MRR deteriorated with increasing pulse-ON time (Figure 80(c)). Figure 80(d) shows that MRR improved by amplifying the rotating speed, because higher rotating speed helped remove chips from the distance between the workpiece and micro-electrode. Figure 80(e) shows that the capacitor was the most significant factor on MRR. MRR increased with increasing capacitor due to the amplified electrical discharge energy transmitted to the workpiece.

Figure 81 illustrates the EWR response graph. Figures 81(a) and 81(b) show that EWR increased with increasing current and pulse-ON time due to the rising amount of heat and energy transmitted to the workpiece for melting and vaporizing that caused microelectrode melting or vaporizing as well. Another reason for the EWR amplification with pulse-ON time is that in micro-EDM, the micro-hole is very small and the low amount of energy for removing material causes overcut, as described in Section 1.10.7.1.1. Hence, the chips cannot be easily removed inside the hole between the microelectrode and workpiece. Some of the sparks took place between these chip and microelectrode that caused to augment wear of the microelectrode. Moreover, the collection of chips inside the micro-hole produces unstable servo operation, which further decreases machining efficiency and increases EWR.
pulse-OFF time, sparks did not occur, so melted and vaporized material solidified to the EDM chips, allowing the chips to be removed from the distance between the microelectrode and workpiece. Increasing pulse-OFF time caused more chips to be removed from the distance between the microelectrode and workpiece. This decreased the amount of sparks that occurred between the microelectrode and chips and increased the amount of sparks between the microelectrode and workpiece. Thus, EWR was reduced by increasing pulse-OFF time (Figure 81(c)). Based on Figure 81, the effect of pulse-ON time on EWR seemed more significant than the other parameters.

1.10.7.1.3 Surface roughness

Figure 82 demonstrates FESEM images presenting the surface quality at the rim (wall) of the micro-holes attained in WC-16%Co composite in different EDM conditions. These pictures were taken by rotating the WC-Co plate inside the FESEM. It was found that there are direct relationships between the micro-hole surface finish, burr-like recast layer at the top surface and MRR, based on observations in Figure 82 and Table 12. Surface roughness enhanced by decreasing the MRR, but it deteriorated by increasing the MRR. The amount of burr-like recast layer at the top surface decreased when the surface roughness enhanced. It can be concluded that the surface roughness.

Figure 82  Comparison of surface quality at the rim of the micro-holes at different conditions.
roughness improved and the burr-like recast layer at the top surface decreased with decreasing current, rotating speed, and capacitor and increasing voltage and pulse-ON time because of decreasing MRR. Current and capacitor were the most significant factors; however, the effect of the capacitor was more prominent than current.

1.10.7.1.4 Micro-crack

The electrical discharge energy increases with the amplification of voltage, current, pulse-ON time, and capacitor, while pulse-OFF time and rotating speed have no effect on the electrical discharge energy according to the formula for calculating electrical energy:\( E = V I_{\text{on}} \) and \( E = \left(1/2\right) CV^2 \). Moreover, the voltage controls the discharge gap between electrode and workpiece. Increasing the voltage will increase the discharge gap. Suitable voltage according to current, pulse-ON time, pulse-OFF time, rotating speed, and capacitor results in better MRR and helps the thermal energy reach the workpiece. When current and pulse-ON time are high, MRR increase with amplifying voltage up to a desired value due to the increased discharge gap and because the chips and debris can easily be removed from this area. Subsequently, the amount of MRR decreases with voltage above the desired value because the discharge gap is larger than the suitable range and less energy reaches the workpiece.

![Figure 83](image-url)
FESES served for taking pictures with 2500 magnification. Figure 83 shows that the amounts of micro-cracks were on the surface in different machining conditions for holes 1–16. Figure 83 demonstrates that pulse-OFF time and rotating speed had no effect on the amount of micro-cracks, because they had no effect on electrical discharge energy. It is clear that the amounts of micro-cracks on holes 5, 6, 15, and 16 were less than on other holes. Larger pictures of these holes (at the end of Figure 83) show the distribution of micro-cracks. Comparing low pulse-ON time (holes 15 and 16) with high pulse-ON time (5 and 6) indicates that pulse-ON time had less effect on changing the amount of micro-cracks because the deference between low and high pulse-ON time (1 and 5 μs) is short. Analyzing low voltage (holes 1 and 3) and high voltage (holes 2 and 4) depicts that voltage was one of the most significant factors on the amount of micro-cracks. Investigating low current (holes 15 and 16) and high current (holes 3 and 4) demonstrates that current was another significant factor affecting the amount of micro-cracks. Studying low capacitor (holes 15 and 16) and high capacitor (holes 1 and 2) represents that the capacitor was another factor determining the amount of micro-cracks. Evidently, the highest amount of micro-cracks appeared in hole 7 (low voltage, low current, high current, high pulse-ON time, and high capacitor), hole 12 (low voltage, low current, high pulse-ON time, and high capacitor), and hole 14 (low voltage, high current, low pulse-ON time, and high capacitor). The least micro-cracks appeared on hole 15 at 90 V voltage, 0.4 A current, 1 μs pulse-ON time,
9 $\mu$s pulse-OFF time, 20 rpm rotating speed, and 0 $\mu$F capacitor. It is clearly observed that more micro-cracks formed when the current, pulse-ON time, and capacitor were at high levels, due to high electrical discharge energy and low thermal conductivity and brittleness of the cemented tungsten carbide. Besides, the amount of micro-cracks decreased when current, pulse-ON time, and capacitor were adjusted to low levels. As described before, the MRR diminished by increasing the voltage because the voltage increases to the more suitable current range of 0.4–5 A, pulse-ON time range of 1–5 $\mu$s, pulse-OFF time range of 1–9 $\mu$s, rotating speed range of 0–20 rpm and capacitor range of 0–0.1 $\mu$F. This caused the workpiece to receive less energy at the high level voltage. It can be concluded that voltage, current, pulse-ON time, and capacitor were the most significant factors contributing to the amount of micro-cracks. The effects of voltage, current, and capacitor were greater than pulse-ON time according to these machining parameter levels.

### 1.10.7.1.5 Material migration

EDX spectrum analysis was performed to analyze the elemental composition of the raw material and recast layer at the wall of the holes. Figure 84 shows the EDX spectrum analysis of the raw material surface and recast layer at the wall of hole 11 as an example. Moreover, Figure 85 demonstrates the elemental composition and percentage of each element for the material and the entire hole’s wall. As seen in Figure 85, W, Co, C, and O elements were present in the workpiece’s raw
Figure 83 (Continued)
Enlargement of picture of hole 15

Enlargement of picture of hole 16

Figure 83  (Continued)
material, while W, Co, C, O, and Al W elements were present in the recast layer at the wall of the micro-holes. Al was added to the recast layer at the wall of the micro-holes, because aluminum powder was used in the dielectric and aluminum migrated to the machined surface and recast layer. The amount of C and O in the recast layer increased when oil-based dielectric was used. On the other hand, the amount of W and Co decreased due to increasing C and O. Moreover, the percentage of W decreased sharply. The lowest percentage of W, approximately the lowest percentage of Co and the highest percentage of C appeared in the recast layer at the wall of hole 9. As a result, it is suggested to use powder with greater elemental composition similarity to the workpiece in the dielectric.

Figure 84  EDX spectrum analysis of the surface on (a) the raw material and (b) the recast layer at the wall of hole 11 as an example.
1.10.8 Conclusions

This work describes EDM and micro-EDM comprehensively and compares the types of pulse generators, electrodes and methods for calculating MRR, EWR, overcut, and surface roughness for these methods. Various fabrication and measurement processes of microelectrode are explained as well. Moreover, this research work was carried out to characterize the effects of micro-EDM drilling of WC−16%Co with a CuW microelectrode by using EDM machine. The results show that:

- Various machining conditions produced different amounts of overcut.
- ANOVA analysis illustrated that MRR increased with amplifying current, rotating speed and capacitor, and decreasing voltage and pulse-ON time. The current and capacitor were the most significant factors, but the effect of the capacitor was greater than current. It can be concluded that the capacitor had the greatest impact on improving MRR. Moreover, EWR increased by increasing current and pulse-ON time and decreasing pulse-OFF time. The effect of pulse-ON time on EWR was more prominent than other parameters.
- It was found there were direct relationships between the surface finish of micro-holes, burr-like recast layer at the top surfaces and MRR. It can be concluded that surface roughness enhanced and the amount of burr-like recast layer at the top surfaces decreased with decreasing current, rotating speed and capacitor, and increasing voltage and pulse-ON time. The current and capacitor were the most significant factors; however, the effect of the capacitor was greater than current.
- Pulse-OFF time and rotating speed had no effect on the amount of micro-cracks due to the insignificant effect on electrical discharge energy. On the other hand, the electrical discharge energy depends on the voltage, current, pulse-ON time, and capacitor. It can be concluded that amount of the micro-cracks decrease with increasing voltage and decreasing current, pulse-ON time and capacitor. The voltage, current, pulse-ON time, and capacitor were significant factors contributing to the amount of micro-cracks. However, the effects of voltage, current, and capacitor were stronger than pulse-ON time.
- Al was added to the recast layer at the wall of the micro-holes, and because aluminum powder was used in the dielectric, aluminum migrated to the machined surface and recast layer. The amount of C and O in the recast layer increased because oil-based dielectric was used. As a result, it is suggested to use powder that is more similar in terms of elemental composition to the workpiece in dielectric. Finally, various machining conditions produced different amounts of overcut.
- In conclusion, EDM can be used confidently for producing micro-holes.

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See also: 1.7 Techniques to Improve EDM Capabilities: A Review

References