Research and Analysis of a Micro EDM System

by

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Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

DECEMBER 2009

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

(Professor T. Nagarajan)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

November 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

SUTHAN ARAVINTHAN SUNDRAJ

ABSTRACT

Micro Electrical Discharge Machining is currently widely used in the manufacturing in a variety of applications, like in the production of micro parts for watches, keyhole surgery, housings for micro surgery, and also tooling inserts for fabrication of micro filters. This study is undertaken with the objective of analyzing various methods of Micro EDM setup and factors and parameters which affect the end product quality and process and to also propose design parameters for production of micro channels with bio-applications. . A brass tube electrode is selected with multiple passes with a resetting of Z-coordinate used as wear compensation method. A R-C generator with 75V and 0.5A with a pulse on time of 12μs is selected to give the best balance between MRR and accuracy. Lastly, de-ionized water is used as a dielectric fluid because its chemically inert and will not pollute the micro channel which is to be used in bio-applications as well as provide a stable MRR.

ACKNOWLEDGMENT

Our first thanks must always go to God Almighty for providing me with the strength and will power to undergo the whole process of Final Year Project.

I wish to express my deepest gratitude to Prof. Dr. T. Nagarajan for his advice, criticism and encouragement during the investigation and fulfillment of this study.

Also many thanks to my friends and family who helped me in so many ways during the course of this project.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Electrical Discharge Machining (or EDM) is a non-conventional machining method which is primarily used for hard metals or those that would be impossible to machine with traditional techniques. It is a successful adaptation of EDM for micromachining from simple holes to complex molds where the discharge energy is reduced to the order of 10^{-6} to 10^{-7} Joules in order to minimize the unit material removal.[6]

It works by removing material via a series of rapidly reoccurring electric arcing discharges between the electrode and the work piece in the presence of an electric field. This process is very versatile and can be used create small or odd-shaped angles, intricate contours or cavities in metals which otherwise impossible to machine economically like titanium, hastelloy, kovar or inconel.[1] An evolution of this process is Micro EDM which is used to fabricate complex three dimensional microstructures.

Micro Electrical Discharge Machining is currently widely used in the manufacturing in a variety of applications, like in the production of micro parts for watches, keyhole surgery, housings for micro surgery, and also tooling inserts for fabrication of micro filters [2]. It was originally applied predominantly in the production. There are many setups available and many factors which influence the process. Realising this, I am undertaking this project with the aim of analyzing and comparing the various setups and influencing factors in regards to Micro EDM.

1.2 OBJECTIVES

i. Analyze various methods of Micro EDM setup

ii. Study the various factors and parameters which affect the end product quality and process.

iii. Propose design parameters of a micro EDM setup for production of micro channels with bio-applications

1.3 SCOPE OF STUDY

Studies will be done to define the differences between conventional EDM and Micro EDM. Then the various types of micro EDM setup are to be gone through as well parameters and factors that affect the process such as dielectric fluid type, electrode wear, material removal rate(MRR), peak current, ignition voltage and type of electrode. These factors are compared and the optimal parameter for each function is chosen for the design of a micro EDM system for the production of microchannels with bio-applications. This study is theoretical in nature in that the optimal parameters as well as setup is studied via the various literature available, and that the results provided will be used by the future researchers to build a physical model.

CHAPTER 2

LITERATURE REVIEW

2.1 Conventional EDM

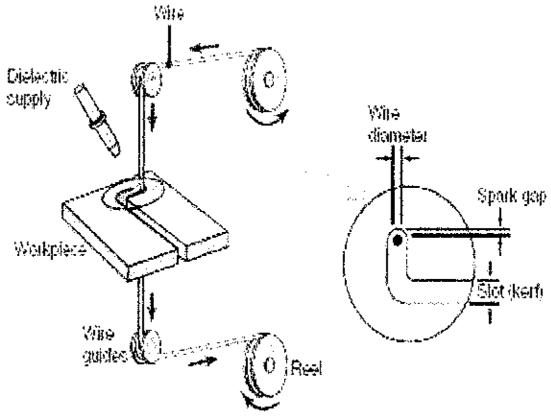


Figure 2.1: Conventional EDM[4]

The principle of electrical-discharge machining (EDM) (also called electrodischarge or spark-erosion machining) is based on the erosion of metals by spark discharges.The basic EDM system consists of a shaped tool (electrode) and the workpiece connected to a DC power supply and placed in a dielectric (electrically nonconducting) fluid.

Electrical-discharge machining has numerous applications, such as the production of dies for forging, extrusion, die casting, injection molding, and large sheet-metal automotive-body components (die-sinking machining centers with computer numerical control).[4]

2.2. Micro EDM

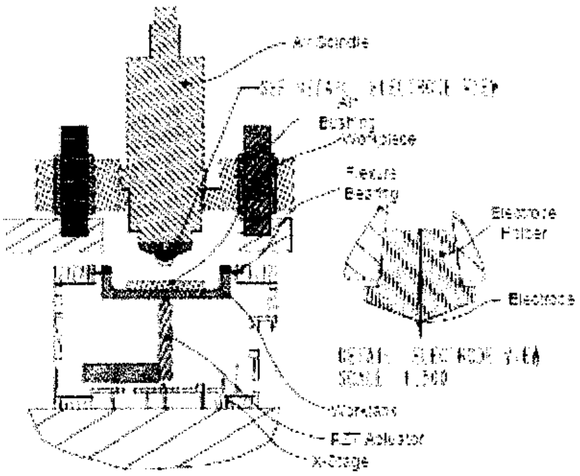


Fig 3: Flexure Concept

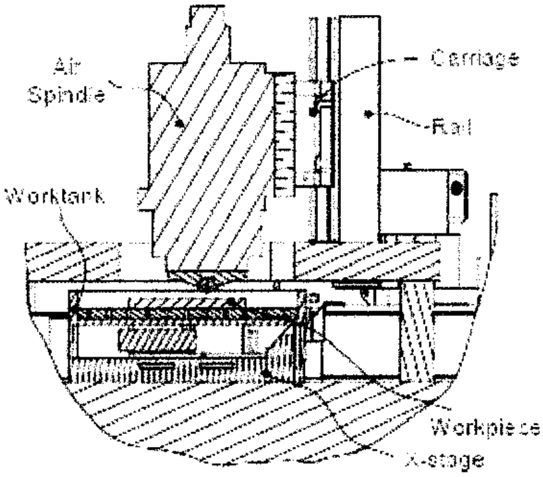


Fig 4: Column Concept

Micro EDM is an innovation of the conventional EDM system. It is primarily used in creation of complex 3D microstructures which otherwise would be impossible to machine accurately. It operates on the same principle as a conventional one but with lower amperage and a more accurate machining on a micro level. There are other differences, in micro EDM applications, the volumetric wear and the ratio between electrode and work piece is not negligible and thus the wear needs to be compensated via replicating electrodes, this is stated by J. Valentine et al,.[3]. The non contact nature of the micro EDM makes it ideal for machining ductile, brittle and super hard material and with appropriate parameters, it is possible to achieve high precision and high quality machining. Even so, according to H.S. Lim *et al*, micro EDM has inherent weaknesses such as high electrode wear and low material removal rate [5]. *King Fu et al* proposes two types of setup in their design paper, i.e the flexure concept and column concept [8]. The flexure concept uses a flexural bearing and PZT actuator for fine motion in the z-direction is illustrated in Fig 3. In this figure, the flexure and actuator are integrated into the x-stage. The flexure supports a round work tank for holding the dielectric fluid and workpiece. A circular flexure is located near the workpiece height in the z direction to reduce Abbe errors. The centers of the worktank, flexure, and actuator are coaxial. A PZT actuator with at least 100 μm travel can be used or a PZT with shorter stroke can be amplified with a mechanism. The electrode tool would be held above the workpiece and rotated with a motor driven, air bearing spindle. A variety of work piece heights is accommodated by pre-adjusting the height of the spindle, which is supported on a plate guided with air bushings.

The column concept however uses a, supports the motorized air bearing spindle on precision (±5 μm over 200 mm rail length) linear guides with recirculation ball (or roller) bearings. The carriage is driven through a servomotor attached to a screw through a flexible coupling and mounted on the support column. In this concept, the course and fine motions are integrated into a single bearing system and actuator in the z direction. The work tank is mounted directly on the x-y plane. The air spindle will require larger travel range (around 200 mm) along the z-axis. Additional Abbe error from the offset roller bearings reduces the accuracy of the machine. Variants on this concept could use other types of linear bearings (such as air bearings) or other drive systems (such as friction drive).

2.4. Flushing and Debris Removal in Micro EDM

K.P. Rajukar[6] states that micro holes with a diameter of about 25 μm is routinely obtained in the range of 15 to 18.The depth of hole drilling may be limited by the difficulties of ejecting generated gaseous bubbles and debris from the narrow discharge gap (several micrometers) during machining. The tool is too small for internal flushing, and external flushing causes vibration of slim tool. The debris concentration results in abnormal discharges (arcs and/or short circuits) leading to unstable machining and excessive tool wear. Several methods such as vibrating the tool/work piece, pre-drilling a hole to allow bubbles and debris to escape from working area, planetary movement of tool have been attempted to improve debris flow.

Also, Muralidhara[11], state that, at a certain depth, direct flushing may not be effective as clearance between the tool and workpiece will be of the order of a few micrometers. And so, when the dielectric fluid flows on the surface of the hole, a pressure drop may occur at the entrance of the hole which maybe sufficient to pull the debris out of the work piece tool interfaces which maybe called indirect flushing. Further, till certain depths, the to and fro motion of the tool will help in flushing the debris out of the hole. However, at higher depths, it is not possible to flush out the debris out of a blind hole while machining with a micro tool. As the depth of machining increases, the debris may settle at the tool-workpiece interface and might be absorbing considerable amounts of heat energy in the subsequent spark discharges. Furthermore, they will be decomposing themselves into finer debris before being finally ejected out of the hole by the to and fro movement of the tool during machining. Hence, only a part of the actual heat energy is being spent in melting the workpiece material as depth increases. Whereas, in the case of tool material, since the tool is in motion during machining, for each spark, most of the energy is absorbed by the tool material which will result in melting and removal of considerable amount of tool material. Hence, at higher depths, the amount of workpiece removal is expected to be to reduced which results in a increase in wear ratio with increase in machining depth.

2.5. Material Removal Rate (MRR)

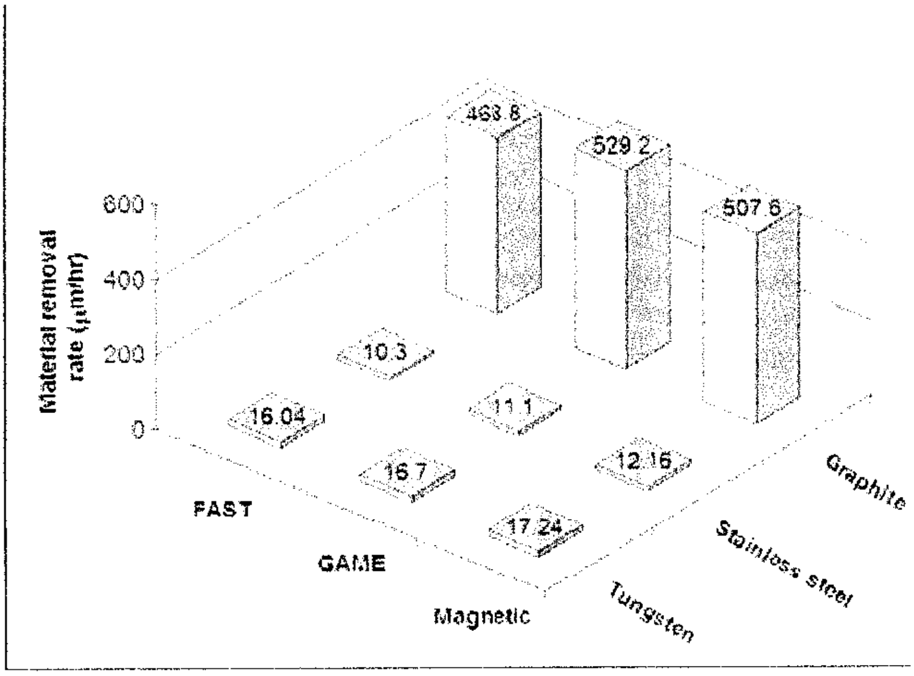
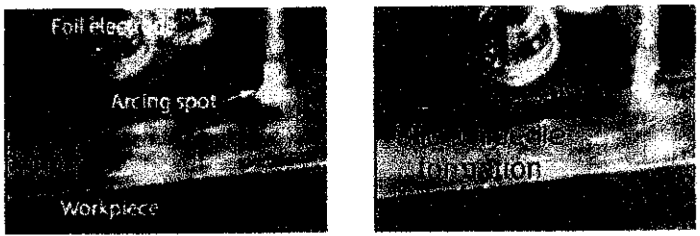


Figure 2.5.1. Material Removal Rate for various electrode materials[7]

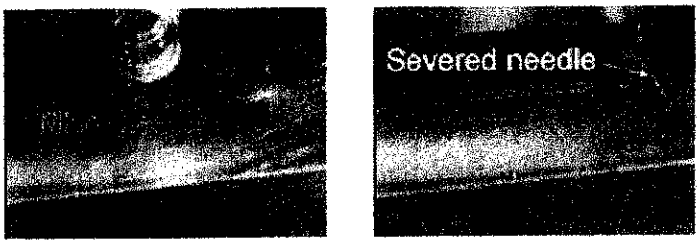
The effect of the tool electrode materials and flushing techniques on the material removal rate is shown above as stated by Murali *et al*[7]

The most conspicuous revelation of the figure above is the performance of graphite as tool electrode material. The MRR achieved using graphite is about 30 to 40 times more than that of the other two materials (tungsten and stainless steel). The reason for this outstanding performance of graphite can be understood by observing the sequence of events during arcing.



(a) arcing begins

(b) micro needle formation



(c) Elongation of micro needle

(d) Breaking of micro needle

Figure 2.5.2: Sequence of events during arcing

In micro EDM using foil electrodes, during the arcing (Fig. 2.5.2.a), the foil material melts and forms a short-circuit by establishing a semi-molten bridge (Fig. 2.5.2.b). The shape looks like a micro needle. During this period, the spindle automatically starts moving up, stretching the micro needle (Fig 2.5.2.c). This withdrawal of spindle continues until the bridge is broken (Fig 2.5.2.d). Once the circuit becomes open, the spindle starts moving down towards the job and the machining resumes. The entire time spent on the up and down motion of the spindle is wastage of machine hour as no machining takes place during this period. When using the metal foils like tungsten and stainless steel, due to their ductility, the needle like bridge keeps stretching itself during the spindle withdrawal and does not break so easily. Sometimes, the stretching may extend up to 2 mm before it severs. In the case of graphite which is brittle and shears away easily, no such "bridge formation" is noticed during arcing. After few μm upward movement of the spindle, the machining resumes immediately. As the non-machining time is minimum, high MRR is achieved using graphite. [7]

2.6. Roughness

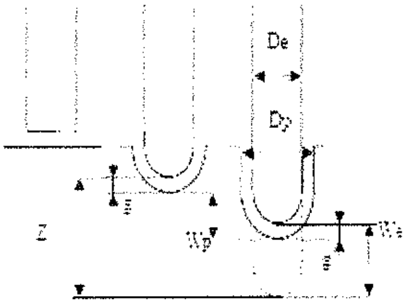
The topography of a work piece can be characterized by four distinct components: form, waviness, roughness and micro-roughness. Form is a component of surface finish with a long wavelength on the work piece. Waviness is a surface texture component varying slowly, depending on the horizontal position. Roughness is a of surface texture component varying rapidly, depending on the horizontal position. Micro-roughness is the fine variation component of surface texture. Various measurements have been performed on work pieces machined with different energy levels. Roughness is an indication of the type of machining used. In fact, given the same electrode diameter, the change of energy is visible in the roughness values. For lower energy levels, the roughness is smaller (around 0.3 Ra), than for higher energy levels. This is essentially due to the fact that the energy per pulse is higher and that the material removal rate is a priority. This implies that the roughness depends essentially on the energy used for erosion. Traditional surface finish analysis consists of studying surface texture roughness and waviness. This implies that form and micro-roughness components do not need to be evaluated. A study of roughness can give an indication on the variability of the flow measured. The friction due to the roughness can be one of the major factors for this variability.[8]

2.7. Volumetric Wear

The volumetric wear is defined as the ratio between the eroded volume from the workpiece *Vp* and the volume
lost due to the wear occurring on the electrode, *Ve* . Measuring each of this volume would allow assessing the
volumetric wear ratio, σ :

$$\sigma = Ve/Vp \quad (1)$$

S.Bigot[10] states that a number of electrode compensation methods depend on the rate of volumetric wear. He also proposes a simple method for volumetric wear estimation in Micro EDM. As stated earlier, after a certain depth of erosion in micro EDM drilling the shape of the rod electrode remains constant. If drilling further from that point down to a target depth Z (graph), we can assume that the volume of wear *Ve* occurring on the electrode is equivalent to a cylinder of diameter *De* (electrode diameter) and of length *We* (eroded length from the electrode).



$$Ve = \frac{\pi \cdot De^2}{4} \cdot We \qquad (2)$$

A similar assumption can be made when using a tubular electrode by taking into account the internal diameter
In this case:

$$Ve = \frac{\pi \cdot \left(De^2 - de^2\right)}{4} \cdot We \qquad (3)$$

Assuming that the spark gap g is constant, Wp being the eroded depth and Dp the diameter of the eroded h
on the workpiece, we can consider that:

$$Wp = Z - We \qquad (4)$$

$$Vp = \frac{\pi \cdot Dp^2}{4} \cdot Wp \qquad (5)$$

Therefore, in the case of a rod electrode, the volumetric wear ratio can be defined as:

$$\sigma = \frac{Ve}{Vp} = \frac{De^2}{Dp^2} \cdot \frac{We}{Wp} = \frac{De^2}{Dp^2} \cdot \frac{1}{\frac{Z}{We} - 1} \qquad (6)$$

And in the case of a tubular electrode:

$$\sigma = \frac{De^2 - de^2}{Dp^2} \cdot \frac{1}{\frac{Z}{We} - 1} \qquad (7)$$

Thus, it is assumed that the volumetric wear ratio is proportional to the ratio Rw:

$$Rw = \frac{1}{\frac{Z}{We} - 1} \qquad (8)$$

For a given Z, *We* can be measured on the machine using a datum plane. After each drilling the electrode tip is brought to the datum plane, to establish electrical contact. The position in Z axis before and after machining determines the loss of length of the electrode, *We* . The drawback with such method is that the electrical contact produces small erosions which would introduce an error into the measurements of We. The deviation in Z position after 100 measurements on the same spot of the same datum plane was measured with an Ø170μm electrode (Figure 2.7). According to the measurements, the error in Z detection brought from 60 electrical contacts (used in next section) should not exceed 1.5μm. In EDM milling, such estimation of the wear ratio is more difficult. The flushing is more stable but the eroding conditions and the electric field intensity are changing regularly due to changes in depths of cut and in passes overlapping.

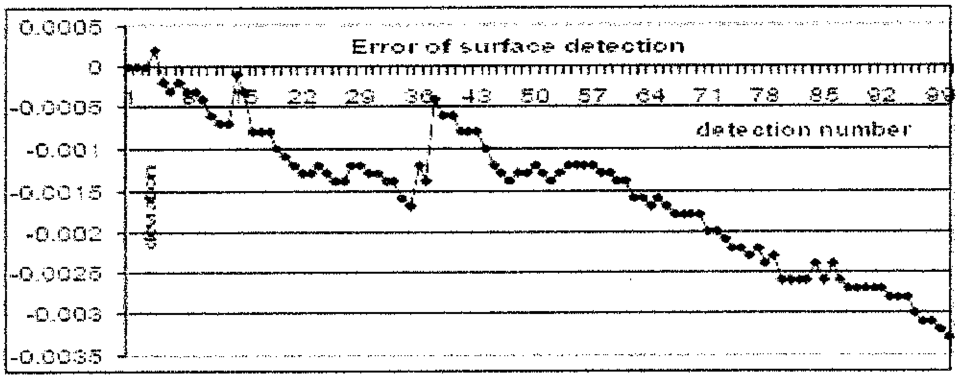


Figure 2.7.1 : Datum Plane erosion after 100 measurements [10]

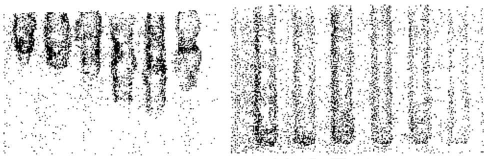


Figure 2.7.2 : Resulting Profile in Aluminum

2.9. Dielectric Fluid

Dielectric fluids serve several important purposes such as[4]:

1. Act as an insulator until the potential is sufficiently high.
2. Provide a cooling medium.
3. Act as a flushing medium and carry away the debris in the gap.

Properties of Dielectric Fluid:

i. Flash Point

   To some extent, flash point is a measurement of the fluids' volatility, and is the minimum temperature at which a fluid will support momentary combustion (a "flash") when in the presence of an ignition source; but *before it will burn continuously* (its "fire point").

ii. Viscosity

   Viscosity is the measure of a fluid's resistance to flow. In general, the *lower* the viscosity rating the easier the fluid is to pump and the better its flushing characteristics, particularly in deep cavities or pockets, fine detail work, etc. (although slightly higher viscosities can perform well in some types of roughing operations).

iii. Pour Point

   Pour point is an indicator of the ability of the fluid to flow freely at cold temperatures, and the temperature given is the lowest at which the fluid will flow. Many dielectric fluids typically become cloudy and more viscous as the temperature approaches their pour point. Pour point can be an important factor in colder climates if the shop is unheated over the weekends or fluid is stored outdoors or in unheated areas; resulting in the operator having to wait until the fluid warms up before it can be used. Most fluids suffer no lasting effects from being cooled to or below their pour point.

iv. Dielectric Strength

Dielectric strength is a measure of the insulating capacity of a given fluid in an EDM environment. Higher dielectric strength helps minimize DC arcing and is frequently touted as an indicator of overall EDM performance.

However, its value in the selection process is negligible since, as soon as the fluid is used, it becomes contaminated with solids from the EDM process itself, significantly altering its dielectric strength and insulating properties. Since typical high-quality dielectric oils have acceptable dielectric strength ratings, and most manufacturers don't publish this information, we don't consider dielectric strength to be a high priority issue.

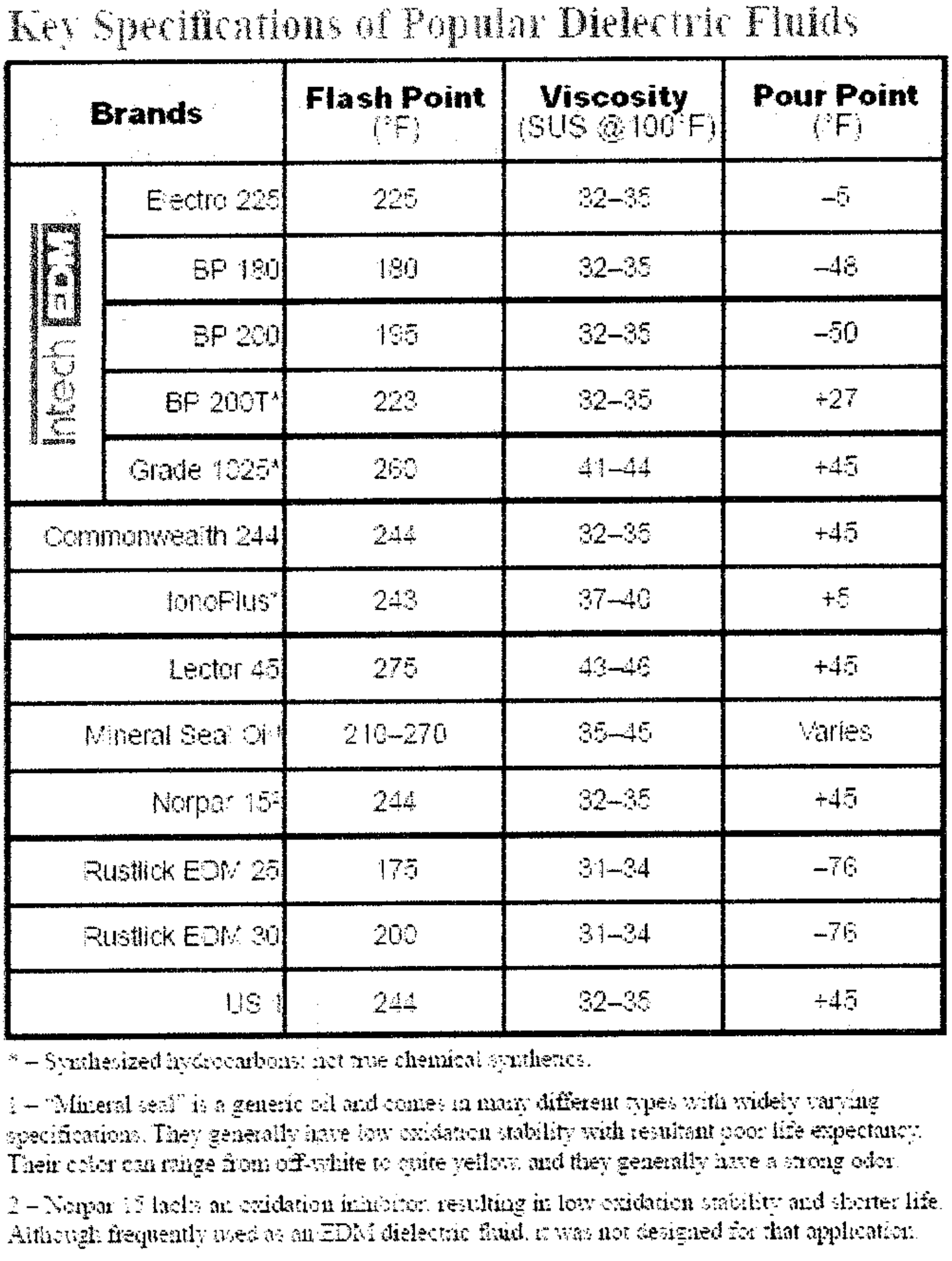
v. Odor

Although the presence of an odor can sometimes indicate excessive evaporation, it is primarily an issue of having an "operator friendly" workplace environment. Most high quality dielectric fluids are either odorless or have a slight but negligible odor.

vi. Oxidation Stability

Oxidation occurs when oxygen attacks and degrades EDM fluids. The process is accelerated by heat, light, and metal catalysts; and the presence of water, acids and solid contaminants. The higher oxidation stability your EDM fluid has, the longer it will last in your system. In a practical sense, how the user handles the fluid has more to do with its life expectancy. Keeping the system as clean as possible, using better filtration, and maintaining lower operating temperatures are all operational factors which can prolong the life of the fluid.

Table 2.1.Key Specifications of Popular Dielectric Fluids



Key Specifications of Popular Dielectric Fluids

Brands		Flash Point (°F)	Viscosity (SUS @100°F)	Pour Point (°F)
Intech EDM	Electro 225	225	32–35	–5
	BP 180	180	32–35	–48
	BP 200	195	32–35	–50
	BP 200T*	223	32–35	+27
	Grade 1025*	260	41–44	+45
Commonwealth 244		244	32–35	+45
IonoPlus*		243	37–40	+5
Lector 45		275	43–46	+45
Mineral Seal Oil[1]		210–270	35–45	Varies
Norpar 15[2]		244	32–35	+45
Rustlick EDM 25		175	31–34	–76
Rustlick EDM 30		200	31–34	–76
US 1		244	32–35	+45

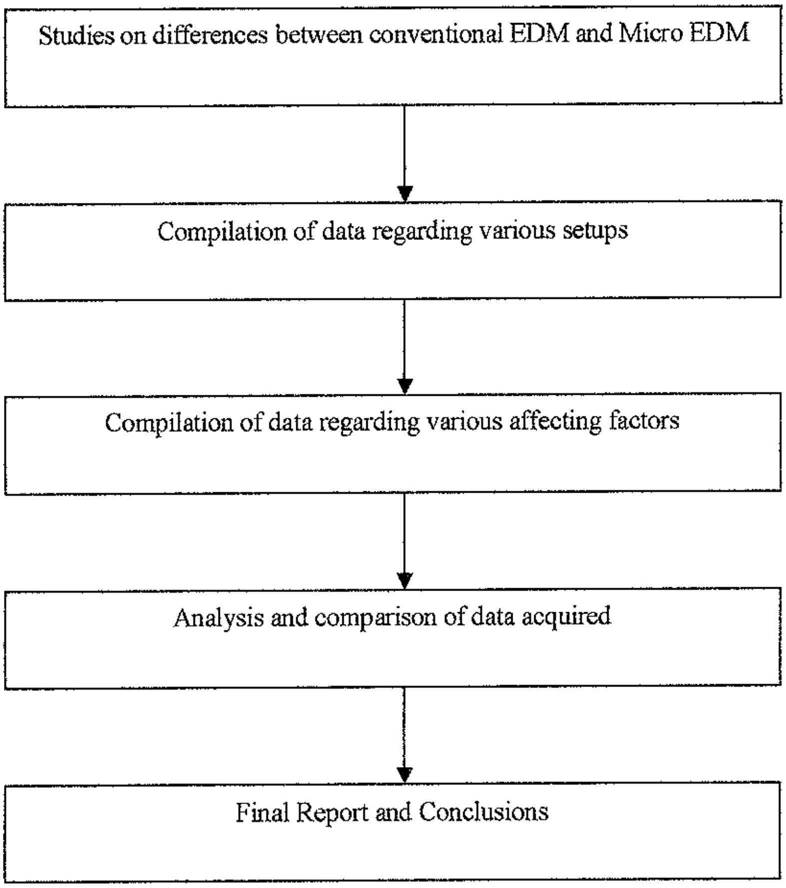
* – Synthesized hydrocarbons: not true chemical synthetics.

1 – "Mineral seal" is a generic oil and comes in many different types with widely varying specifications. They generally have low oxidation stability with resultant poor life expectancy. Their color can range from off-white to quite yellow, and they generally have a strong odor.

2 – Norpar 15 lacks an oxidation inhibitor, resulting in low oxidation stability and shorter life. Although frequently used as an EDM dielectric fluid, it was not designed for that application.

CHAPTER 3

METHODOLOGY



CHAPTER 4
RESULTS AND DISCUSSION

4.1. Electrode Wear

Aluminium and brass have much lower melting points than tool steel and the grain structure consists of much larger grains. With the same spark energy, when work pieces made from aluminium and brass are machined, more material will be melted and, therefore, larger pieces of material will float in the gaps as debris than for steel. When using a rod electrode to erode a hole in soft materials like aluminium and brass, the flushing conditions deteriorates rapidly after reaching a certain depth and the larger the debris, the more difficult it will be to flush them out of the sparking area. From that point onwards, the debris starts causing sparking on the side of the electrode. This breaks the debris into smaller pieces and, finally, they are flushed out of the sparking area. This explains the sudden change in electrode wear behaviour, high rate of electrode wear and distortion of the holes, as shown in Figure 4.1.2. If a tubular electrode is employed, the flushing conditions do not change much for the whole depth. In spite of the size of the debris, they are forced out of the working area by the constant dielectric flow through the tube and the amounts of electrode wear and variations in wear behaviour are much smaller.

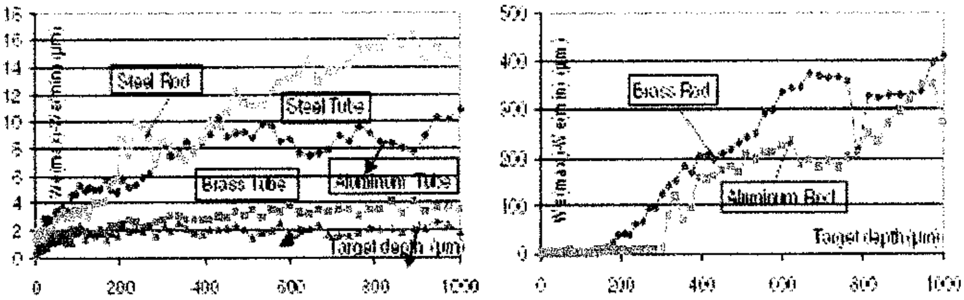


Figure 4.1.1 : Variation in electrode wear

Figure 4.1.1 shows an investigation of tube and rod electrode wear in micro EDM drilling. The figure shows the values of M^{z}_{dif} , where M^{z}_{dif} is the largest difference between the largest and smallest wear present, for the six holes at each targeted depth for each workpiece material and electrode type. M^{z}_{dif} is used to indicate the variation in electrode wear in the same sparking conditions.[17]

When using a rod electrode with brass and aluminium work pieces (Fig. 4.1.1.b), the differences in wear measurements start increasing dramatically from a certain depth. This is mainly because of the deteriorated flushing conditions and due to the strong stochastic character shown the measurements for brass and aluminium does not lead to useful conclusions regarding variations in the amount of wear and the wear ratio. In the case of the steel workpiece, the flushing conditions do not have such a dramatic effect as explained above, but in comparison to the tubular electrode, the rod electrode shows an increased variation in the wear ratio with the depth of the hole (Fig. 4.1.1.a). With the tubular electrode used on the three workpiece materials, the variation in the wear ratio after a certain depth shows a tendency to stabilise (Fig. 4.1.1.a).

From this several results can be drawn where firstly it must be stated that in Micro EDM unlike conventional EDM the variations in wear ratio are not negligible. Therefore, usual compensation methods for electrode wear cannot be used as the usual methods use the assumption that the ratio is fixed. Therefore, any compensation method that is to be used must allow for machining tolerance which is based on the variation of the volumetric wear ratio.
Different electrodes exhibit different types of wear accordingly. Referring to the figure 4.1.2, showing the electrode wear ratio and its effects on process modelling and process capability [17]:

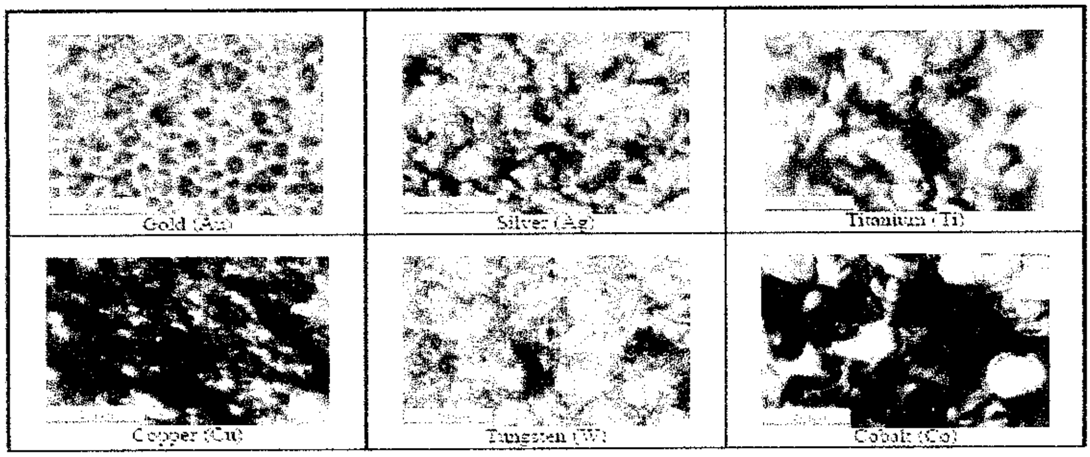


Figure 4.1.2. : image of eroded electrodes(anode) post process[12]

Before the above images were taken, they were cleaned in an ultrasonic bath to remove existing debris from the process. Figure 4.1.2 highlights qualitative topographic differences, if any, induced by the different materials. The shape, so the size of craters is different for the different materials. Craters on the Cobalt and Titanium electrodes are easily visible. However the size of the craters on the Silver, Tungsten and Copper electrodes seems to be smaller. There are also small craters at the surface of the Gold electrode. These images confirm that the energy distribution for different materials will be different and the conclusion is that even with the same machining conditions, materials are working differently, contingent on their own physical characteristics. Therefore, different types of electrode material exhibit different rates of electrode wear and knowing these rates is crucial in determining machinability within the specified tolerances. Also from this it is clear that, when using any new combination of electrode/workpiece materials, tests should be done on the machine to measure the wear ratio and assess its repeatability. The results should be used to justify the chosen compensation method and enable the production of more accurate micro parts.

Due to the fact that electrode wear plays a huge role in Micro EDM, there are several methods to manage the varying electrode wear. K.P Rajukar[6] states that Tool wear in EDM occurs due to the fact that every spark produced in EDM removes material from both work piece and tool as well. This results in unpredictable tool life and inconsistent component dimensions. Understanding the electrode wear process and influencing factors is the key to more accurate and more reliable micro EDM process. The tool wear in micro EDM is mainly influenced by polarity and thermal properties of electrode materials. He also investigated the effect of thermal properties on electrode wear and discovered that the boiling point in addition to the melting point plays a role in the wear ratio. He also states that factors like poor flushing in a deep hole are difficult to control and assess. This could result in a wrong estimation of wear ratio and produced depth. Another factor which affects tool wear is the current wavelength.

Also according to K.P.Rajukar[6], there are two methods to compensate for tool wear, i.e linear compensation and uniform wear method. The linear compensation method is where the tool is fed towards the workpiece and to compensate for the tool wear after it has moved a certain distance. Uniform wear method however, includes both tool path design rules and tool wear compensation. This method can ensure uniform tool wear at the tool tip of the electrode.

S.Bigot[10] states that EDM drilling the electrode tends to follow a constant shape generation during machining. Also, it was observed that the constant shape is obtained after drilling down to a depth of around 180 μm as per the figure below. This specific shape can be explained by the fact that at the beginning of the erosion the electric field intensity is not uniform. It is stronger at the corners resulting in more erosion. We assume that the obtained shape represents a uniform electric field intensity distribution. In EDM milling, due to electrode wear, the depth of cut constantly changes, therefore the electrode shape evolution is even more difficult to predict.

Also referring to, D.T.Pham et al, [2004], Micro EDM – recent developments and research issues, another method for managing electrode wear is proposed. One solution is to repeat the process a number of times with new or reground micro-electrodes until the required profile is obtained. This is called the multiple electrode strategy. The main drawback is that it can be time consuming and difficult to predict the number of needed electrodes. The problems created by electrode wear become more complicated when machining complex 3D micro-cavities. Either wear is too severe to allow the use of complex-shaped electrodes in a classical die-sinking process or electrode geometry is impossible. Thus, for the production of micro-3D cavities, the use of micro-EDM milling with simple shape-electrodes might be the preferred strategy. A basic method is to use a layer-by-layer machining strategy that compensates for wear during the machining of each layer by constant electrode feeding in the Z-axis, based on estimation of the wear ratio. It is assumed that eroding of sufficiently thin layers would ensure that wear only occurs on the face of the electrode but not on the sides. Very accurate estimation of the amount of wear is required, because an error in the estimation would have a cumulative effect through the layers. However, even when using a very small layer thickness, side wear is not negligible and introduces errors in the machined profile.

The methods proposed above however, have an issue in that the main problem is that they rely highly on the accuracy of the wear estimation models they employ. Thus, with these methods under-estimation of the amount of wear could easily result in overcutting of the cavity.

Therefore, D.T.Pham et al[27], have proposed a new method in which the main idea of the proposed method is to machine a cavity using a number of different milling paths, each covering the complete volume of the cavity, and, before starting each path, to reset the Z co-ordinate $Z_{contact}$ at which the tip of the electrode first establishes electrical contact with the workpiece. If electrode dressing is performed at the beginning of a path, the remaining length of dressed electrode should be long enough, at least equal to the depth of the cavity, to avoid erosion with the undressed part of the electrode. By resetting $Z_{contact}$ before each path, the amount of wear from the previous path can be estimated, which gives an indication of the need for further machining or electrode dressing. The machining process can continue until no more wear is registered on the electrode.

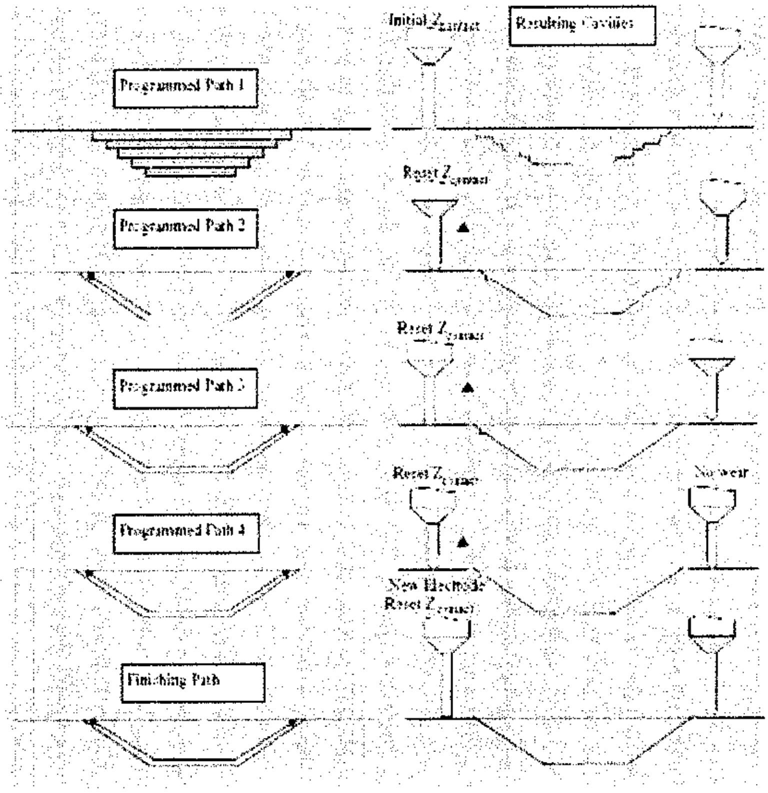


Figure 4.1.3: proposed strategy for wear compensation [17]

After the first machining pass (Path 1 in Fig 4.1.3.), due to wear appearing on the side and the face of the electrode,the cavity is only partially eroded. $Z_{contact}$ is reset and a path is selected for the next machining pass. Once there is no more wear on the electrode (for example after Path 4 in Fig. 4.1.3.), one or more finishing passes with a newly dressed electrode might need to be performed in order to complete the machining (finishing path in Fig. 4.1.3).The main drawback of this method is the time wasted when an electrode follows a path already eroded. Considering the speed of movement when no erosion occurs in comparison with the speed of movement when eroding, this time loss is relatively small. However, to reduce the number of electrodes that might be needed to complete a cavity; each path should be specially designed to optimize the removal of material.

4.2. Electrical Pulse Condition

According to K.Liu et al, micro-scale EDM machining, conventionally used transistor type pulse generators are no longer suitable because of the long delay time for the discharge current to diminish to zero after detecting the occurrence of a discharge. Thus, it is very difficult to obtain discharge duration of a few ns and the energy input for each discharge is not optimal. Generally, resistance-capacitance (RC)-based generators are widely employed for the pulse generation in micro-machining. It can easily generate pulses with high peak current values and short duration, allowing efficient and accurate material removal, and meanwhile achieving the required surface quality. For the RC-based generator, when the dielectric within the gap breaks down, the energy stored in the RC circuit releases over the electrodes and makes the current flow. In the case of micro-machining, this energy should be small enough to obtain less discharge current[28].

The source energy of electro discharge between the tool electrode and the workpiece is an electric one of which power is determined by supplied current and voltage. So the electro discharge energy is expressed as Eq. (1).

$$E = VIT \qquad (1)$$

V= voltage, I= current. T= temperature

In the pulse type current, if it is substituted time T to an intermittent one with frequency, Eq. (1) is changed into the following expression:

$$E_p = V_p I_p t_{on} \frac{1}{t_{on}+t_{off}} \qquad (2)$$

V_p: voltage of a single pulse, I_p: current of a single pulse, t_{on}: pulse on-time, t_{off}: pulse off-time.

Eq. (2) can be transformed into the expression for material removal rate by multiplication of machining property. Hence, the expression can be written as:

$$MRR = \alpha V_p I_p t_{on} \frac{1}{t_{on}+t_{off}} \qquad (3)$$

where α is the removal constant of a material. The constant means removal volume of a material per unit electric power. It is certain from Eq. (3) that the parameters of voltage, current, and pulse On-time are proportional to the material removal rate. The frequency of pulse is also proportional to that, but the parameter is not perfectly independent of the pulse On-time. The reason is that the pulse Off-time is needed sufficiently depending on the power of a single pulse. The equation also shows that a shorter duration is more advantageous than a longer one to make accurate machining under the same condition. Since the removal rate is the same but the removal volume per pulse is smaller in the shorter pulse, if the ratio of pulse On-time to Off-time is the same.

Referring to, influences of pulsed power conditioning on the machining properties in Micro EDM [23], the following figures are extracted:

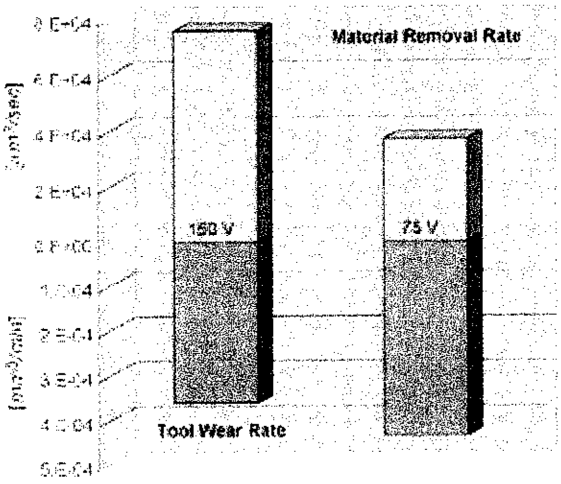


Figure 4.2.1: Material removal and tool removal rate vs. EDM pulse voltage[23]

As can be seen from the figure, the material removal rate doubles as the input voltage is grown. The result agrees quite well with the theoretical expression. In the case of the tool wear rate, a decrease of the input voltage causes the machining time to be increase due to the decrease of the removal rate, and it increases the tool wear rate as well.

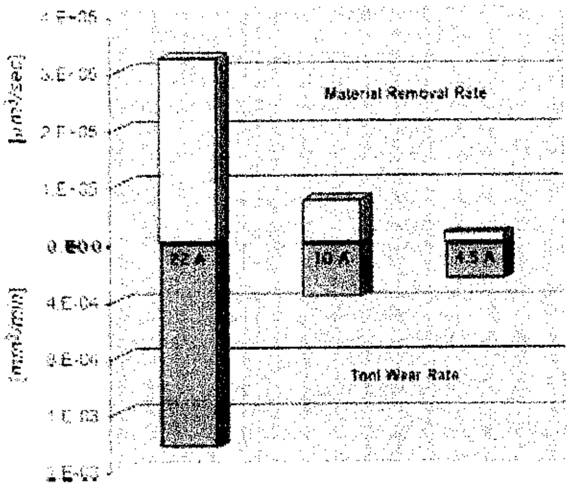


Figure 4.2.2 : Material removal and tool removal rate vs. EDM pulse current

On the other hand, the removal rate is increased as a square value to an increase of the input current as shown in the Fig . The reason can be found from the transformation of Eq. (3). The parameter of VI can be changed into I^2R and the R is the resistance of a tool-workpiece. The tool wear rate is also increased with an increase of the input current.

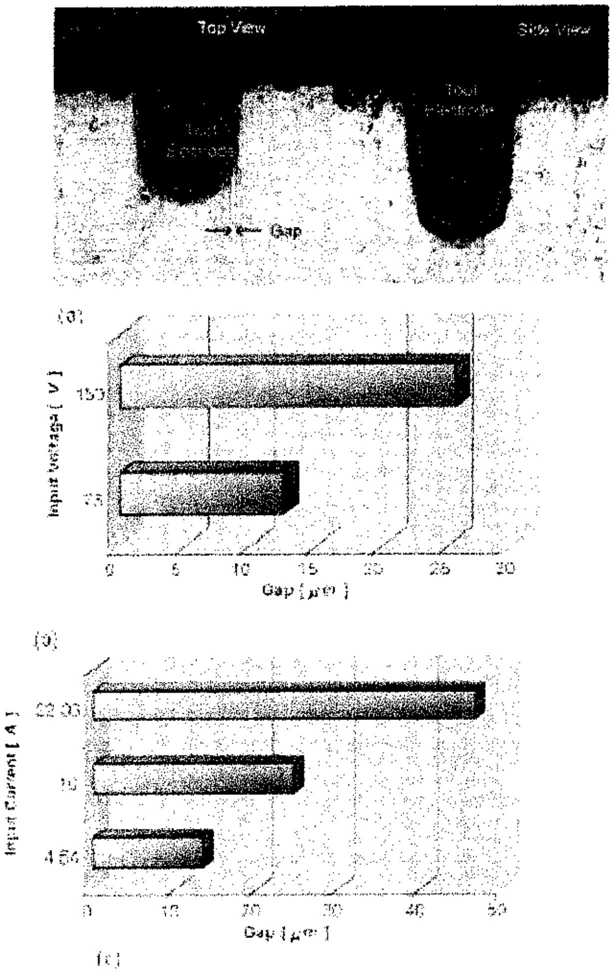


Figure 4.2.3 : Gap distance between a tool and machined surface : (a) Gap distance between tool and a machined surface, (b) Result for the voltage parameter, (c) Result for the current parameter

The gap between the tool and the machined surface was measured to investigate form accuracy as shown Fig. (a). Fig. (b) and (c) show gaps between the tool and the workpiece under various experimental conditions of voltage and current. It can be seen that the gap is widened with an increase of voltage and current. The value of gap variation almost coincides with the value ratio of the input parameter.

Seong Monsen et al, conducted experiments to determine to define the connection between the material removal rate and pulse duration.

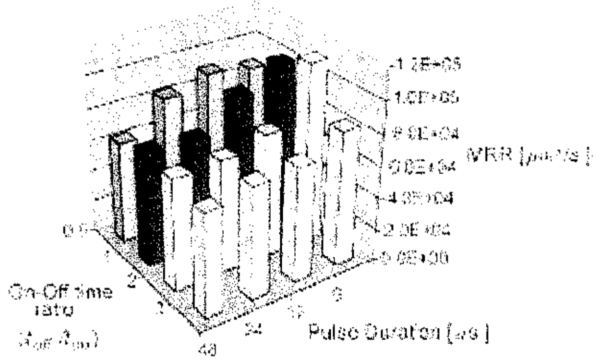


Figure 4.2.4 : Material removal rate vs. On-Off conditions of EDM pulse

In their experiment, the pulse is fixed at 10A the value of t_{off}/ t_{on} is in the range of 0.5-3 and the duration varies from 6μs to 48μs at the respective ratio. Fig. shows the material removal rates depending on each condition. According to Eq. (3), the removal rate should be theoretically equivalent under the same ratio of Off-time to On-time, but the value appears definitely difference with the duration of On-time. The shorter pulse-on duration is, the more quickly material is removed. Moreover the removal rate has a trend of increase with decrease of the t_{off}/t_{on} ratio, but it is not dominant in the overall experimental conditions.

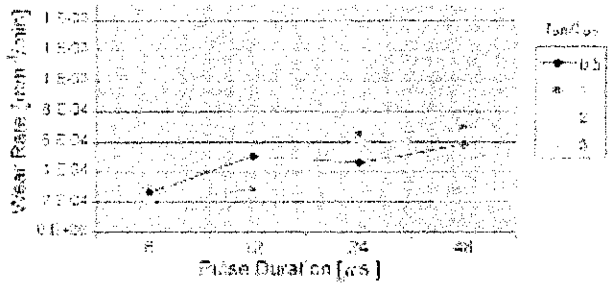


Figure 4.2.5 : Tool wear rate vs. On-Off conditions of EDM pulse

It clearly appears that the tool wear is decreased with reduction of pulse On-time. In the case of a shorter duration, oversupply of electrical input compared to removal volume per pulse. In other words, the relatively shorter EDM pulse is more efficient in energy consumption the material removal rate is greater than the case of a relatively longer one. Nevertheless, the tool wear is smaller than the latter. It may indicate the efficiency of energy consumption. In the material removal rate, though the supply electrical power is increased twice, the removed volume per unit time does not become double but goes up only about 20%. It means there is an oversupply of electrical input compared to removal volume per pulse. In other words, the relatively shorter EDM pulse is more efficient in energy consumption.

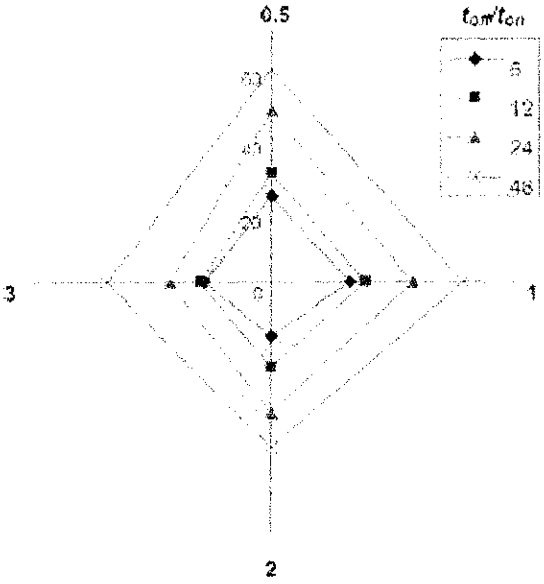


Figure 4.2.6: Gap distance between a tool and a machined surface for the various pulse On-Off condition.

The gap between the tool and the machined surface was measured to investigate the relation with form accuracy and the ratio of a pulse On–Off time. It can be seen from Fig. 4.2.6 that the accuracy is higher in the case of shorter pulse duration over all ranges of these experimental conditions. In the comparison of a mutual different t_{off}/t_{on} ratio, the gap shows a trend of decrease with increase of pulse Off-time. It can be supposed that the appearance is due to the difference of cooling time of material depending on the pulse Off-time duration

4.3. Dielectric fluids.

Generally, kerosene is used as the dielectric fluid in most of the die-sinking EDM systems; but, the dielectric properties of kerosene are degraded when machining is done for long time. Also, owing to hydrocarbon oil, kerosene decomposes at very high temperature of discharge energy and pollutes the air around the machining setup. The adhesion of carbon particles on the work surface also restricts the efficient and stable discharge and further reduces the material removal rate (MRR). Due to these drawbacks and for the sake of industrial safety and ensuring non polluted environment, investigations are going on using other types of dielectric fluids to overcome the above-mentioned problems. Deionized water is one of the supplementary dielectrics that can be used efficiently in micro-EDM. Not only that, investigations have been performed by many researchers with powder-mixed dielectrics composed of different size of powder particles with different concentration to explore their effects on the micro-EDM performances and machined surface integrity [19].

Referring to the figures taken from, G.Kibria et al,[2009], comparative study of different dielectrics for micro EDM performance during microhole machining of Ti-6Al-4V alloy.

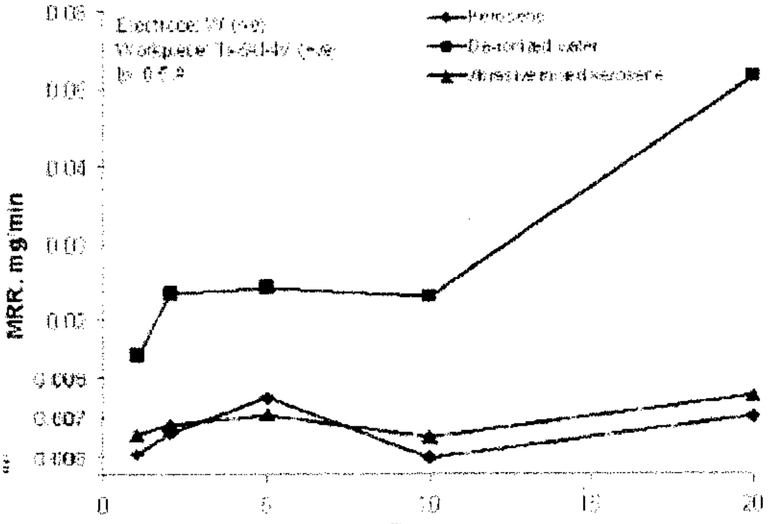


Figure 4.3.1 : Variation of material removal rate(MRR) with pulse duration(T_{on}) at I_p=0.5A[19]

This figure reveals that MRR is high with deionized water than kerosene for at I_p=0.5A during experimentation. As kerosene dielectric is a chemical compound of carbon and hydrogen, it decomposes during sparking due to pulsed discharge energy and produces titanium carbide (TiC) layer on the workpiece surface. Similarly, deionized water produces titanium oxide (TiO2) layer. Since, TiC has a higher melting temperature (3,150°C) than that of TiO2 (1,750°C), larger discharge energy is required for improving the material removal rate using kerosene than that of deionized water. Additionally, when machining is done by mixing B_4C powder additives in kerosene dielectric, it is clearly seen that MRR increases with the increase of pulse duration at constant peak current of 0.5 A. Also the MRR with powder-mixed dielectrics is larger compared to machining with pure kerosene and deionized water at higher pulse

duration discharge settings. The increase of MRR with the increase of pulse duration using B_4C mixed kerosene is due

to increase of spark discharge time, i.e., longer effective machining time per pulse. The presence of boron carbide additive in kerosene further helps in uniform distribution of discharge energy and better conduction of discharge current, thereby enabling better machining condition.. So, it is concluded that the addition of carbide powder particles in dielectrics prevails better machining efficiency than the pure dielectrics due to uniform distribution of discharge energy in the machining zone.[19]

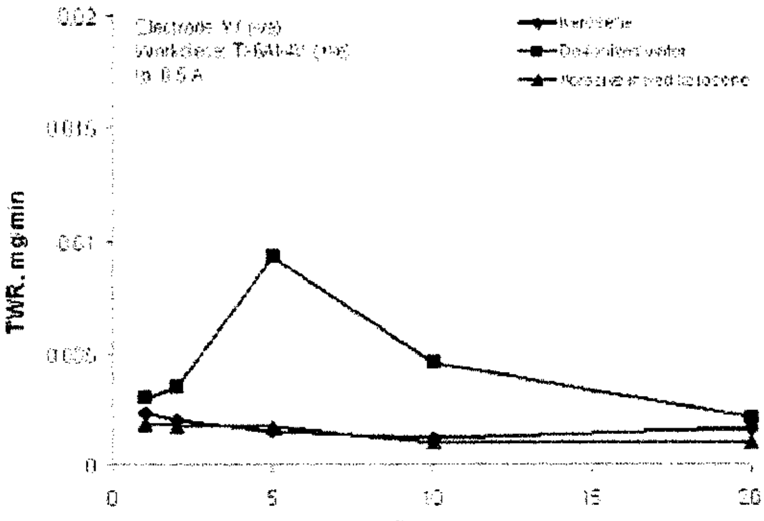


Figure 4.3.2: Variation of tool wear rate (TWR) with pulse duration(T_{on}) at I_p=0.5A[19]

This figure reveals that TWR is high using deionized water compared to machining with kerosene dielectric. Kerosene decomposes at elevated temperature and produces carbon particles that adhere and form a protective layer over tool electrode surface. These carbon particles restrict the rapid wear of the tool. But deionized water does not produce any carbon during machining and formation of protective carbon layer on the tool surface does not arise. Moreover, more burning occurs in the discharge zone, enabling more tool wear with deionized water dielectric.

Furthermore, it is revealed from the same figure that tool wear rate associated with B4C-mixed kerosene is less compared to machining with pure kerosene at peak current of 0.5A. When machining is done with boron carbide abrasive mixed kerosene dielectric, the tool wear is less due to the presence of more number of carbon particles evolving from the decomposition of kerosene dielectric as well as boron carbide abrasive in the machining zone.

It is also found that machining combined with boron carbide powder-mixed deionized water results in less tool wear compared to pure deionized water due to adhesion of carbon particles from boron carbide powder on the tool surface, which restricts tool wear to certain extent.[19]

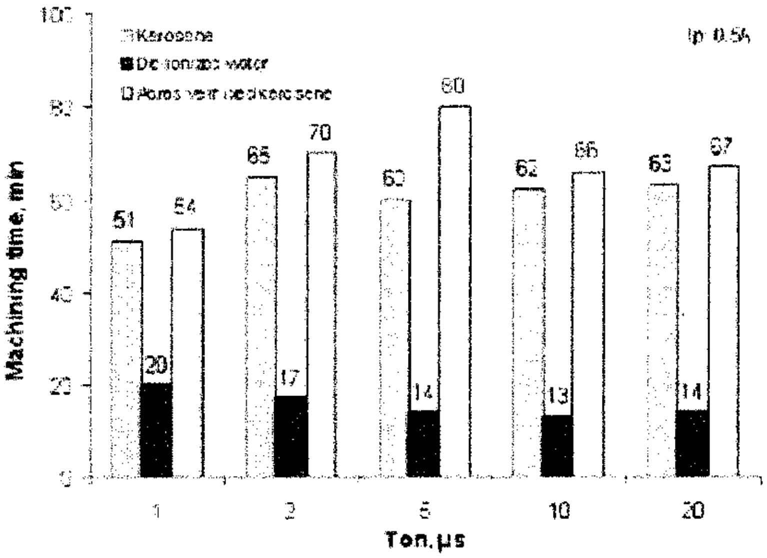


Figure 4.3.3 : Variation of machining time(MT) with pulse duration(T_{on}) at I_p=0.5A[19]

Referring to the figure above, G.Kibria et al, performed machining time tests, by studying the time required to machine a workpiece of 1mm thickness at various pulse times. From the figure, it can be seen that pure deionized water results in low time compared to other dielectrics, i.e., kerosene and B_4Cmixed dielectrics to fabricate microholes in Ti-6Al-4V plate. As boron carbide mixed kerosene supplies more carbide particles at the machining zone, so there is more chances of formation of TiC layer on the workpiece surface which is why it takes longer time for machining. Further, as B_4C-mixed dielectrics increases the gap size, the distance traveled by the tool will also increase and this results in longer machining time although additive particles encourage the uniform distribution of discharge energy which enables better machining efficiency.

4.4 Partial Design of a Micro EDM system for the production of micro channels with bio-applications

Biocompatibility is the ability to exist along living tissue without harming them. Therefore titanium alloy (Ti6Al4V) is used as a workpiece because of its high bio-compatibility[30]

4.4.1.Electrode Wear

In order to increase accuracy of the micro channel dimensions, the electrode wear should be stable to prevent inconsistencies in the dimensions. Therefore, brass tube electrodes should be used in this setup so that the wear rate does not fluctuate too much so that the variations are within tolerance levels.

For electrode wear compensation, D.T.Pham et al[27]'s method of compensation can be used where the micro channel is machined using a number of different milling paths, each covering the complete volume of the cavity, and, before starting each path, to reset the Z co-ordinate $Z_{contact}$ at which the tip of the electrode first establishes electrical contact with the workpiece. If electrode dressing is performed at the beginning of a path, the remaining length of dressed electrode should be long enough, at least equal to the depth of the cavity, to avoid erosion with the undressed part of the electrode. By resetting $Z_{contact}$ before each path, the amount of wear from the previous path can be estimated, which gives an indication of the need for further machining or electrode dressing. The machining process can continue until no more wear is registered on the electrode. The usage of this method can ensure that the electrode wear rate is well compensated for and can prevent irregularities in the micro channel dimensions.

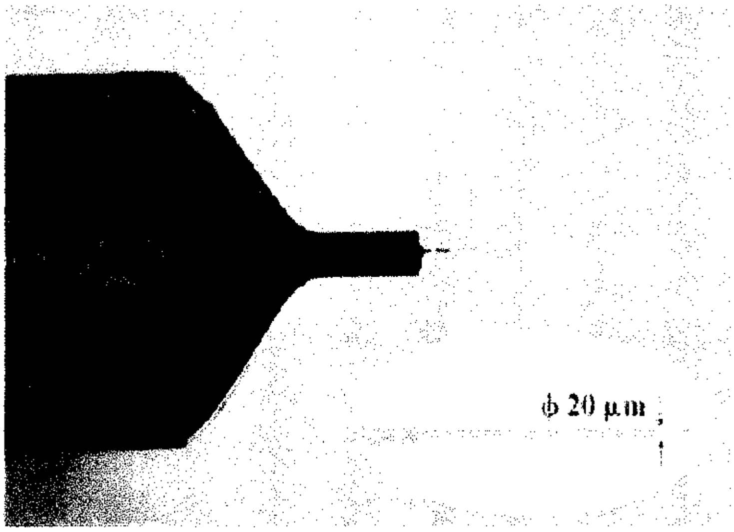


Figure 4.4.1 : Brass tube electrode of diameter 20μm is fabricated from the standard 300μm diameter brass electrode[30]

4.4.1 Electrical Pulse Condition

A resistance-capacitance based generator is to be used for the pulse generation in micro-machining. It can easily generate pulses with high peak current values and short duration, allowing efficient and accurate material removal, and meanwhile achieving the required surface quality. For the RC-based generator, when the dielectric within the gap breaks down, the energy stored in the RC circuit releases over the electrodes and makes the current flow. In the case of micro-machining, this energy should be small enough to obtain less discharge current.

A voltage of 75V is used as a too high voltage will result in a higher material removal rate and where it would cause increased roughness in the micro channels. Also a comparatively shorter pulse on duration is profitable to make accurate machining with a higher removal rate and a lower tool wear rate. Therefore, a pulse time of 12μs is chosen it gives the best balance with a t_{off}/t_{on} ratio of 3 as a short pulse time saves more energy as less energy is required to. Also a current of 0.5A is chosen. Thus,
electro discharge energy, E can be calculated as:

$$E_p = V_p I_p t_{on} \frac{1}{t_{on}+t_{off}} \qquad (1)$$

$$Ep = 12V * 0.5A*12\mu s* \frac{1}{12\mu s+36\mu s}$$

$$=1.5J$$

4.4.2 Dielectric Fluid

To improve accuracy, the MRR should not be too high and therefore ionized water with B_4C abrasives added is used. Even though kerosene has a similar MRR, due to the application of this project in the bio field it is not allowable. Also, owing to hydrocarbon oil, kerosene decomposes at very high temperature of discharge energy and pollutes the air around the machining setup. The adhesion of carbon particles on the work surface also restricts the efficient and stable discharge and further reduces the material removal rate (MRR). Due to these drawbacks and for the sake of industrial safety and ensuring a non polluted environment kerosene is not applicable in this situation.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Comparing the proposed methods of electrode wear above, it can be seen that the choice of method will depend on the tolerances required. If the tolerances are high, a simple method as proposed such the linear compensation method will be sufficient to ensure the tolerances are met. However, where low tolerances are required using a number of different milling paths, each covering the complete volume of the cavity, and, before starting each path, to reset the Z co-ordinate $Z_{contact}$ at which the tip of the electrode first establishes electrical contact with the workpiece. Usage of this method is certainly complicated, and therefore the practical application of this method should be in situations where very low tolerances are needed.

Referring to the data compiled earlier regarding pulse conditions, it can be seen that voltage, current, and pulse on/off time of the EDM power are important in deciding the material removal rate. Voltage and current are proportional to the material rate whereas only current is proportional to the tool wear ratio. The gap between the machined surface and tool, increases with the increase in the voltage and current but it is inversely proportional to the length of pulse on time. Also, it is clear that the duration of the pulse on/off time clearly affects the machining properties such as material removal rate, tool wear rate, and machining accuracy. A comparatively shorter pulse duration time, is advantageous in order to make accurate machining with a higher removal rate and lower tool wear ratio.

From the data above, several assertions can be made, where it can be seen that material removal rate is high with deionized water dielectric compared to pure kerosene. This is due to the formation of oxide (TiO_2) layer on workpiece surface when deionized water is used, which melts in lower discharge energy compared to melting of carbide (TiC) formed in case of kerosene. This TiC layer restricts the workpiece material to melt and vaporize during machining. Although B_4C additive mixed kerosene has not shown remarkable improvement in MRR, but the mixing of B_4C with deionized water shows an excellent increase in MRR due to the efficient distribution of discharge and increase in machining efficiency.

The kerosene decomposes at higher temperature due to larger discharge energy and produces carbon particles that adhere to the microtool electrode surface and this phenomenon restricts rapid tool wear during machining using kerosene; but when deionized water is used, no such adhesion occurs. Hence, tool wear is higher with deionized water compared to kerosene. Also, TWR is more when B_4C-mixed deionized water is used compared to pure kerosene. Also it should be noted that pure deionized water results in excellent machining efficiency in comparison to kerosene as well as B_4C mixed dielectrics. Also, the addition of B_4C abrasive in dielectrics results in more machining time compared to pure dielectrics.

To design the parameters studied above for the application of production of micro channels with bio-applications, only the parameters studied in the results and discussion are analyzed i.e : electrode type and wear compensation method, electrical pulse condition and dielectric fluid. A brass tube electrode is selected with multiple passes with a resetting of Z-coordinate used as wear compensation method. A R-C generator with 75V and 0.5A with a pulse on time of 12µs is selected to give the best balance between MRR and accuracy. Lastly, de-ionized water with B_4C abrasives is added and is used as a dielectric fluid because its chemically inert and will not pollute the micro channel which is to be used in bio-applications as well as provide a stable MRR.

From all this data collected certainly in the future someone else can further pursue this title and make a physical model which embodies all the best parameters as per discussed in this final report and perhaps be able to solve other problems that plague Micro EDM as they are expensive and heavy. Due to this, their application in Malaysia is quite limited even though there is potential. Therefore anyone able to solve these problems would contribute highly to the manufacturing industry in Malaysia with regard to micro applications.

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29. T.Kawakami, M. Kunieda, 2006, Study on the factors that determine the minimum machinable size in Micro EDM
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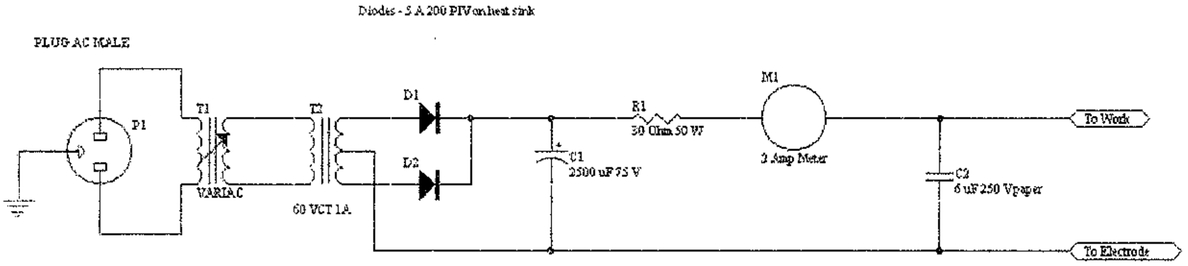
APPENDIX

EXPERIMENTAL MODEL

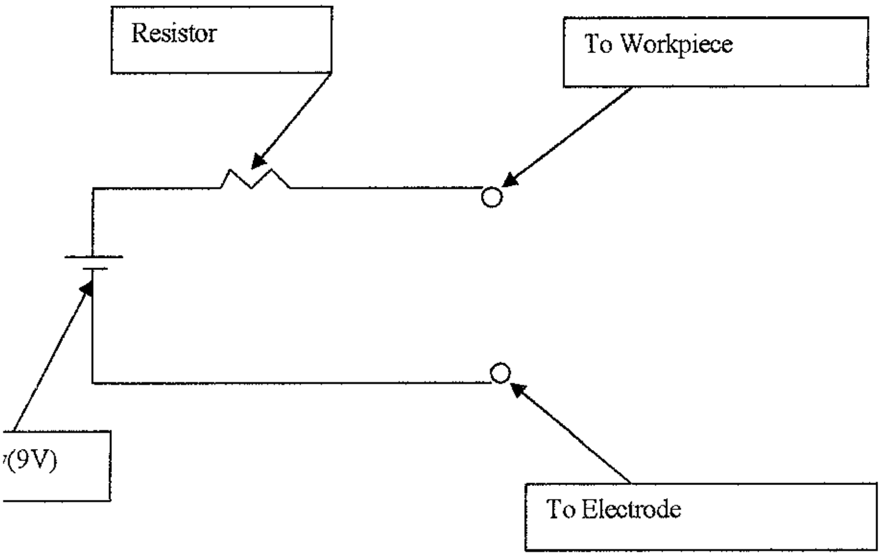
Original Circuit[13](for conventional EDM)



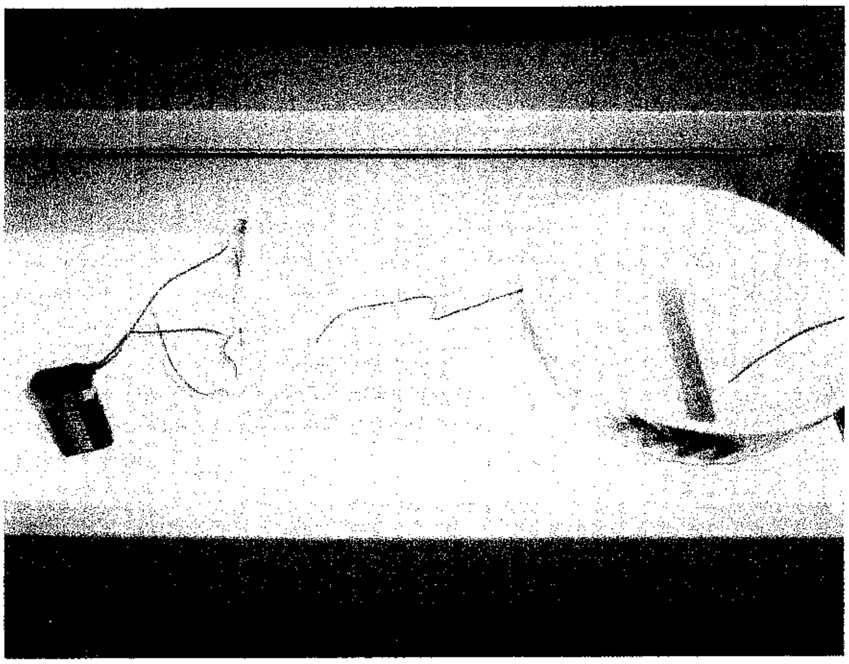
Explanation:

A variac (variable autotransformer) is used to adjust output voltage. A 200 Watt variac (1-2 Amps at 110 V) is quite adequate. A step-down transformer, which provides isolation, is the next component. The one I used was center-tapped, allowing the use of 2 rectifiers. If your choice of transformer does not have the center tap, or the voltage is too low when using it, you could use a bridge rectifier on the two outer connections of the secondary to get higher voltage. A filter capacitor provides smoothing of the DC voltage produced. A resistor allows the electrode to short to the work without blowing fuses, and also moderates the flow of current from the raw DC supply to the EDM capacitor and electrode. Choose a resistance that will cause a short circuit current at least twice the desired EDM current at the selected voltage. Then, make sure the wattage is sufficient to prevent the resistor burning up during a few seconds of short circuit. With the DC supply set to 30 Volts, a short would draw approximately 1 Amp, and since P=I^^2 * R, that is about 30 W, using a 30 Ohm Resistor. The ammeter shows current into the EDM capacitor. The EDM capacitor delivers short bursts of very high current whenever the insulating film of the EDM fluid gets very thin between the electrode and workpiece.

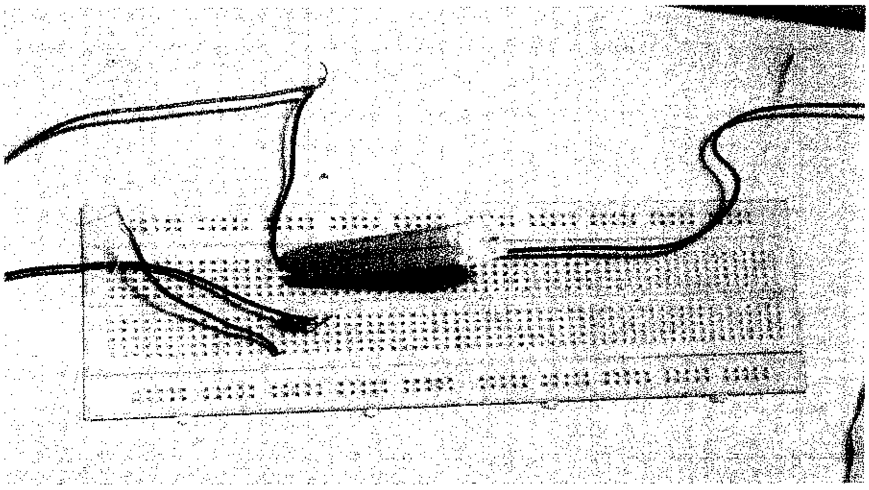
Modified Circuit (For Micro EDM and using a DC power source)



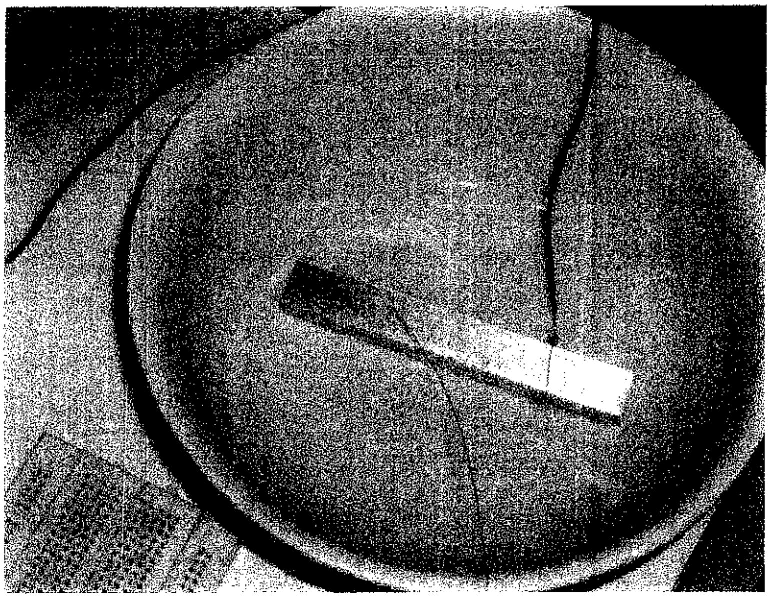
The power source required for Micro EDM is many times smaller than Conventional EDM, therefore only a 9V battery is used. Furthermore, battery is a DC(Direct Current) source. Therefore, rectifying diodes are not needed as well as the two capacitors as their function to smooth out the current is not needed.



The whole experimental setup for Micro EDM



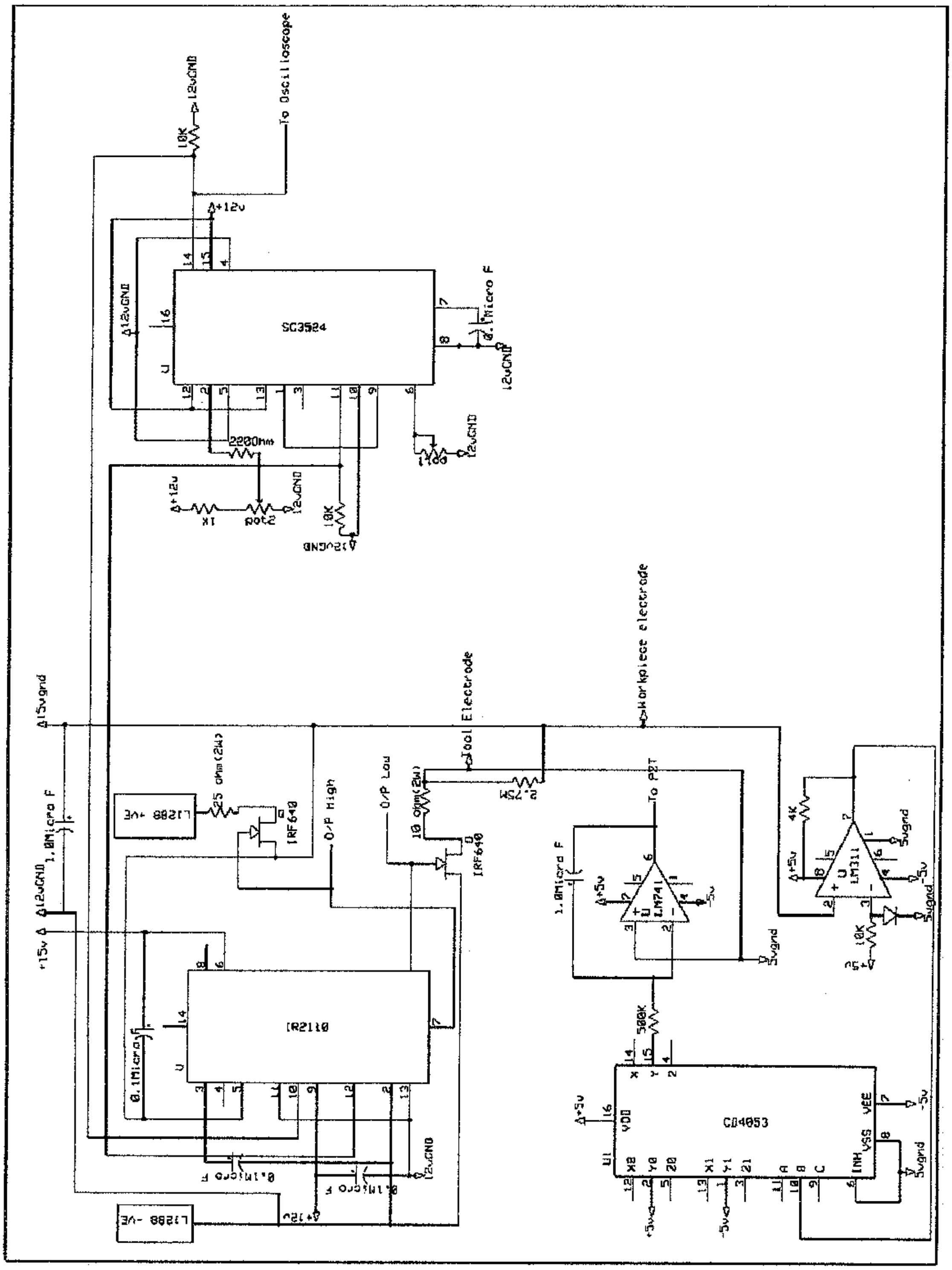
The circuit assembly on the breadboard



The workpiece attached to the electrodes

Theoretical Values

Resistance(Ohm)	Voltage(Volt)	Amperage(Ampere)
10	9	0.90
33	9	0.27
47	9	0.19


SG3524
IR2110
CD4053
LM741
LM311
IRF640
IRF640
To Oscilloscope
Tool Electrode
Workpiece electrode
To PZT
O/P High
O/P Low
LT288 +VE
LT288 -VE
25 ohm(2W)
10 ohm(2W)
2.25M
1.0Micro F
1.0Micro F
0.1Micro F
0.1Micro F
0.1Micro F
0.1Micro F
2200hm
pot2
1K
10K
10K
10K
100
4K
500K
+12v
12vGND
+15v
15vgnd
5vgnd
+5v
-5v
VDD
VEE
VSS
INH