DESIGN AND DEVELOPMENT OF A MICRO-EDM USING MICRO ACTUATOR TOOL FEED CONTROL SYSTEM

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FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled "Design and Development of a Micro-EDM using Micro-Actuator Tool Feed Control System" is written by Mohd. Hishammudin Bin Donnie. I have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering.

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Examiner   Signature

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Report submitted in partial fulfillment of the requirements for the award of the degree of
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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this project and in my opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature

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Date : 6 DECEMBER 2010

STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. This project has not been accepted for any degree and is not concurrently submitted for award of other degree.

Signature

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Dedicated to my parents and my family members that have supported me throughout this project and as well as my supervisor.

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ABSTRACT

This thesis deals with the development of the Micro-EDM with Micro-Actuator Tool Feed Control System. The objective of this thesis is to fabricate the machine by implementing the sensor by using the Amplified Piezoelectric Actuator as tool feed control system. The thesis describes the components that are essential to fabricate the machine. This research is done because there is a huge demand in the production of microstructures by a non-traditional method which is known as Micro-EDM. Micro-EDM process is based on the thermoelectric energy between the workpiece and the electrode. This research also conducts a study about the dielectric flushing that is one of the most important parameters in Micro-EDM. The dielectric flushing removes the unwanted waste metal particles that will disrupt the machining process and will eventually affect the machining accuracy and precision. The development of the control circuit is also discussed in this thesis whereas the circuit is analyzed in OrCAD software to confirm the circuit validity for the use of controlling the Micro-EDM. Micro-EDM is a newly developed method to produce micro-parts which is in the range of 50µm - 100µm. Micro-EDM is an efficient machining process for the fabrication of micro-metal hole with various advantages resulting from its characteristics of non-contact and thermal process. A pulse discharges occur in a small gap between the process of melting and vaporization. In this thesis describes the characteristics, the material removal rate, and the dielectric circulation system that are essential in the Micro-EDM process.

ABSTRAK

Tesis ini berkaitan dengan pembangunan Mikro-EDM dengan Alat Sistem Kawalan Mikro-Aktuator. Tujuan tesis ini adalah untuk mebuat mesin ini dengan menerapkan sensor dengan menggunakan Aktuator yang diperkuatkan dengan Piezoelektrik sebagai sistem kawalannya. Tesis ini menggambarkan bahagian yang penting untuk membentuk mesin ini. Penelitian ini dilakukan kerana ada permintaan yang besar dalam pengeluaran barangan mikrostruktur dengan kaedah baru yang dikenali sebagai Mikro-EDM. Proses Mikro-EDM ini berdasarkan pada tenaga termoelektrik antara specimen dan elektrod. Penyelidikan ini juga merupakan kajian tentang proses peredaran dielektrik yang merupakan salah satu parameter yang penting dalam Mikro-EDM. Proses peredaran dielektrik ini menghilangkan sisa logam yang tidak diingini yang akan mengganggu proses mesin dan akhirnya akan mempengaruhi ketepatan mesin dan kepersisannya. Pembangunan rangkain kawalan juga dibahaskan dalam tesis ini dan rangkaian tersebut telah dianalisis dalam perisian Orcad untuk mengesahkan kesahihan litar untuk kegunaan mengendalikan mesin Mikro-EDM ini. Mikro-EDM adalah kaedah baru yang dibangunkan untuk menghasilkan bahagian mikro yang berada dalam julat 50µm-100µm. Mikro-EDM ini merupakan proses pemesinan yang cekap untuk pembuatan lubang-lubang mikro-logam yang dihasilkan dari ciri-ciri tidak berhubung dengan specimen dan proses terma. Pembuangan pulsa terjadi di celah kecil antara proses pelakuran dan pengewapan. Ciri-ciri kadar penghapusan bahan, dan sistem peredaran dielektrik yang merupakan satu elemen yang penting dalam proses Mikro-EDM turut digambarkan di dalam thesis ini.

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LIST OF SYMBOLS

υ	Volumetric Wear Ratio
α	Removal constant for material
g_e	Spark Gap
Re	Reynolds Number
Fr	Froude Number
A_c	Cross-sectional flow area
L_c	Characteristic Length
$\dot{V}$	Volume Flow Rate
y_c	Critical Depth

LIST OF FIGURES

LIST OF ABBREVIATIONS

EDM	Electrical Discharge Machining
PZT	Piezoelectric Actuator
CAD	Computer-aided drafting
CAE	Computer-aided engineering
DOF	Degree-of-freedom
MRI	Magnetic Resonance Imaging
CNC	Computer Numerical Control
CMA	Ceramic Multilayer Actuator
MRR	Material Removal Rate
TWR	Tool Wear Rate
WEDM	Wire Electrical Discharge Machining
APA	Amplified Piezoelectric Actuator
DC	Direct Current
WEDG	Wire-Electrical Discharge Grinding
W	Tungsten
WC	Tungsten Carbide
CAM	Computer-Aided Manufacturing
UWM	Uniform Wear Method
PWM	Pulse Width Modulator
MOFSET	Metal-Oxide-Semiconductor Field-Effect Transistor
Et. Al.	And others
OpAmp	Operational Amplifier
UTS	Ultimate Tensile Strength

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In recent years the demand of micro parts has been increasing and the use of machining in micro scale became of outmost important. Recent studies have been conducted to optimize the full capacity of micro machining. In producing micro parts the use of Micro-EDM has been vastly used. Micro-EDM is produced micro parts for aerospace applications and small scale parts such as producing micro holes etc.

Micro machining has been renowned to produce high aspect ratio micro products and there is a huge demand in the production of micro-structures by this non-traditional method which is known as Micro-EDM (Electrical Discharge Machining). Micro-EDM concept is based on the thermoelectric energy between the workpiece and electrode. The working principles of EDM is based on the conversion if electrical discharge energy into thermal energy through a series of discrete electrical discharges occurring between the electrode and workpiece while immersed in the dielectric fluid (Kumar et. al., 2009). Micro-EDM is an efficient machining process for the fabrication of micro-metal hole with various advantages resulting from its characteristic of non-contact and thermal process. A pulse discharge occurs in a small gap between the workpiece and the electrode at the same time removes the unwanted material from the parent metal through the process of melting and vaporization.

Piezoelectric actuator is one of the most important mechanism in a Micro-EDM because a piezoelectric actuator controls the displacement of the Z-axis movement of the tool feed mechanism. Piezoelectric actuators are important in optics, space, aircraft, biomedical, and manufacturing field whereas in those field there is a strong need for a compact, robust, and efficient positioning mechanism that offer high precision, short response time, low power consumption, low electromagnetic interference and multiple degree of freedom (Claeyssen et. al., 2002).Piezoelectric is the best candidate to build a servo-feed mechanism since it has high precision and low power consumptions. In additional to that a piezoelectric actuator has fast response time where fast response is crucial in order to avoid short-circuit between the tool electrode and the workpiece when the erosion process takes place.

1.2 PROBLEM STATEMENT

Recent developments in Micro-EDM have made Micro machining a crucial process in manufacturing microproducts. Micro-EDM is needed for a high precision machining where high precision machining is needed to produce microproducts that is essential in the future. In machining process there are countless problems that can reduce the quality of the product and that will affect the cost of the machining. In micro-EDM drilling, producing blind holes is stated as a problem because wear will constantly reduce the length of the electrode. Problems regarding the electrode wear will affect the erosion process where when eroding down to a fixed depth, the real depth of the hole will be significantly small. It becomes more complicated when machining complex 3D micro-cavities. High wear rate will cause more frequent wire breaks. This is because wear reduces the cross section of the micro-wire therefore the maximum tension the wire can take reduces as the cross section area of the micro-wire decreases.This will affect the spark gap where the spark gap area will change as the electrode moves down feeding in the Z-axis direction.The absence of the dielectric flushing will result in low precision machining processes. The decomposition on the tool electrode and the workpiece will make the machining process hard to commence because the decomposed carbon particles will block the surface that is supposed to be machined. The machining process will become more complicated since the tool electrode is expensive to fabricate the machining process must be done accurately in order to lower the machining cost.

1.3 OBJECTIVES OF THE RESEARCH

The objectives of the study are:

(i) To study the piezoelectric-actuator as a tool feed control system
(ii) To design the reservoir tank and circulation system
(iii) To determine the comparison of material removal rate between theoretical and experimental

1.4 SCOPE OF PROJECT

This study is to develop a Micro-EDM with micro actuator tool feed system by using a piezoelectric actuator. The piezoelectric is a sensor that has high positioning precision, high resolution, quick response to feedback and it can also acts as both actuator and sensor. The required model of the piezoelectric actuator is analyzed from Cedrat Technologies and the preferred model for the experiments will be purchased. Previous design uses a servo motor as the tool feed control system where the servo motor is not accurate because the maximum displacement is not as small as the piezoelectric actuator where the piezoelectric actuator scale is in micro-scale.

Based on previous research circuitry on micro-EDM the circuit will be evaluated and produced based on the needs of our project. The study and interpretation of a rectifier circuit of Micro-EDM will be conducted in this project. Dielectric flushing is essential in Micro-machining because dielectric flushing will remove the waste metal particle that decomposes on the tool electrode. A dielectric circulation system will be proposed in this study and based on the design of the reservoir tank (dielectric tank). The circulation system is chosen based on the most suitable flushing system that can flush the dielectric fluid and cast away the unwanted waste metal particle after the machining processes. The circulation system in the tank is to ensure the dielectric fluid can flush the waste metal particles and cool the electrode.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Micro Electrical Discharge machining is quite similar with the principals of Electrical Discharge Machining. Electro discharge machining (EDM) is a thermal process that uses electrical discharges to erode electrically conductive materials. EDM has a high capability of machining the accurate cavities of dies and molds (Zarepur et. al., 2007) EDM is an effective technique in the production of micro components that are smaller than 100µm. EDM is a contactless process that exerts every small force on both the work piece and tool electrode. EDM is a process that provides an alternative method to produce microstructures. It is also states that the micro EDM is similar to the principal of macro EDM where the process mechanism is based on an electro-thermal process that relies on a discharge through a dielectric in order to supply heat to the surface of the work piece. The current causes the heating of the dielectric, the work piece, and the electrode. The dielectric forms a channel of partially ionized gas. The discharge power is dissipated in the plasma channel with amount between 2% and 10%. The channel acts as a heat source on the surface of the work piece. Then the work piece is locally heated beyond its melting point and removed after the material ejected solidifies within the cooler dielectric medium. The significant difference between micro and macro EDM is the plasma channel radius (diameter). In macro EDM the plasma size is larger by several orders of magnitude than the plasma channel radius. The size of the plasma channel can be changed by the pulse duration because the channel radius increases as the time increases. If the pulse duration time allows the channel to expand until it is larger than the electrode diameter, the rate of its expansion will change.

2.2 PRINCIPLE OF MICRO-EDM

Micro EDM is based on a simple theory, when two electrodes is separated by a dielectric medium, come closer to each other, the dielectric medium that is initially non-conductive breaks down and becomes conductive (Murali et. al., 2004). During this period sparks will be generated between the electrodes. The thermal energy released will be used for the material removal by melting and evaporation. By precisely controlling the amount energy released, it is possible to machine micro features on any electrically conductive material.

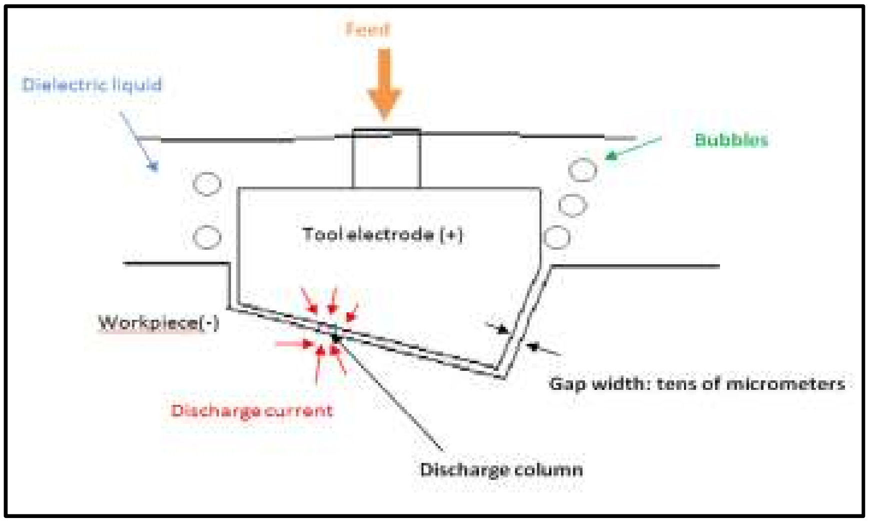


Figure 2.1: Concept of EDM

In the gap filled of insulating medium most preferable a dielectric liquid such as hydrocarbon oil or de-ionized water between the tool and electrode occurs the discharging of the pulsed arc (Kunieda et. al., 2005). The insulating medium is to avoid the electrolysis effects on the electrodes during the EDM process. The electrode shape is copied with an offset equal to the gap size and the liquid will be selected to minimize the gap in order to obtain precise machining. To make sure it is safe, a certain gap width is needed to avoid short circuiting especially for electrodes that are sensitive to vibration or deformation is used. Initially, a high voltage current is needed to discharge in order to overcome the dielectric breakdown strength of the small gap. Formed between the electrodes is a channel of plasma (ionized and electrically conductive gas with high temperature) and it will develops further depends on the discharge durations.

Discharge occurs at high frequencies between 10^3 and 10^6 hertz since the metal removal per discharge is very small. For every pulse, discharge occurs at a particular location where the electrode materials are evaporated or ejected in the molten phase then a small crater is generated both on the tool electrode and workpiece surfaces. The removed material are then cooled and re-solidified in the dielectric liquid forming several hundreds of spherical debris particles which will be flushed away from the gap by the dielectric flow.

At the end of the discharge duration, the temperature of the plasma and the electrode surfaces that is in contact of the plasma rapidly drops, resulting in the recombination of ions and electrons also the recovery of the dielectric breakdown strength. To obtain stable condition in EDM, it is important for the next pulse discharge occur at a spot distanced sufficiently far from the previous discharge location. This is because the previous location will result in having a small gap and it is contaminated with debris particles which may weaken the dielectric breakdown strength of the liquid. The time interval for the next discharge pulse should be long so that the plasma that is generated by the previous discharge can be fully de-ionized and the dielectric breakdown strength around the previous discharge location can be recovered by the time the next voltage charge is applied. If happens that the discharges occurs at the same location, resulting in thermal overheating and non-uniform erosion of the workpiece.

2.3 TYPES OF EDM PROCESS

2.3.1 Sinking EDM

The sinking electrical discharge machining is as shown in Figure 2.2. The workpiece can be formed either by replication of a shaped tool electrode or by 3-Dimensional movement of a simple electrode similar to milling or we can use the combination of the both the methods. Normally we use copper or graphite as the electrode material. The numerical control monitors the gap conditions and synchronously controls the different axes and the pulse generator. The dielectric liquid is filtrated to remove debris particles and decomposition products. Hydrocarbons dielectrics are normally used since the surface roughness is better and tool electrode wear is lower compared to the de-ionized water.

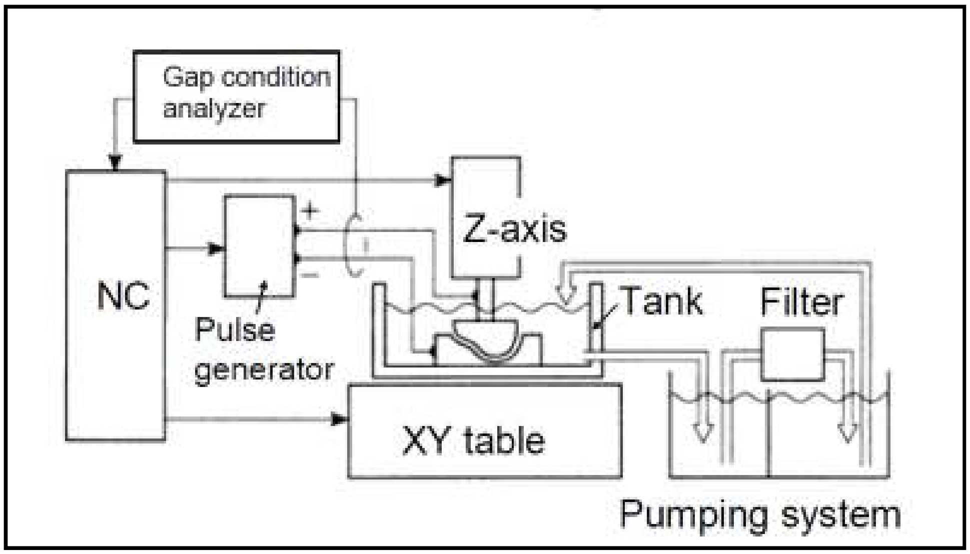


Figure 2.2: Sinking Electrical Discharge Machining

Source: Kunieda et. al. (2004)

2.3.2 Wire EDM

In the figure below outlines the wire electrical discharge machining (WEDM method). Wire electrode methods can cut complicated shapes like a wire sawing machine. Normally the wire electrode is brass wire or coated steel wires but in case of thin wires tungsten or molybdenum wires are used. Since we can change the orientation of the wire by controlling the horizontal position of the upper wire guide relative to the lower guide all types of surfaces can be cut. Discharge current with a high peak value over a short duration of time are used, both the upper and lower feeding brush are supplied with current to obtain a quick rise in the discharge current by reducing the inductance in order to avoid breakage due to Joule heating. To reduce vibration and deflection tension is applied to the wire resulting in deteriorated cutting accuracies.

Water is the most often used as the dielectric liquid but its specific electrical conductivity should be decreased using de-ionizing resins to avoid electrolysis and to keep high open voltage.

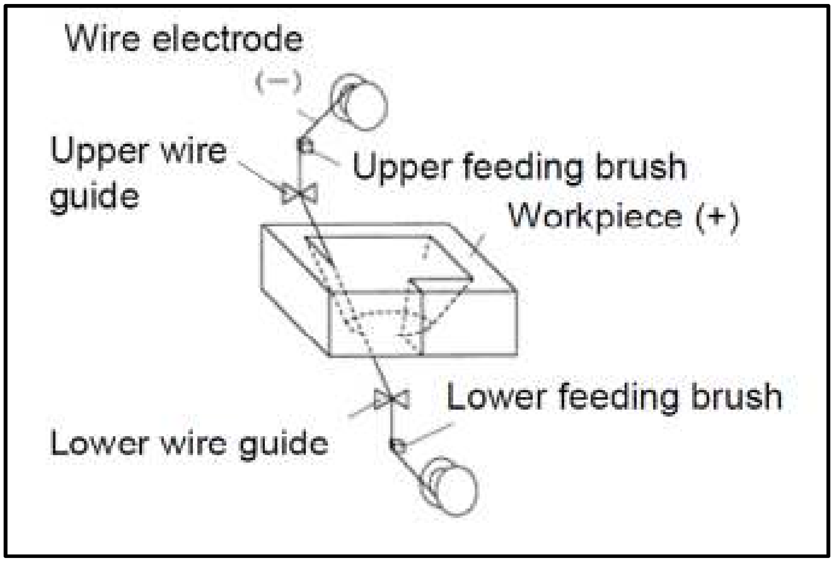


Figure 2.3: Wire Electrical Discharge Machining

Source: Kunieda et. al. (2004)

2.4 DIELECTRIC FLUIDS

In micro electrical discharge (MEDM) machining the most important thing to ensure the efficiency of the feed is the dielectric fluids. In MEDM the dielectric fluid acts as a cutting medium to improve surface roughness, corrosion resistance and wear resistance. In most die-sinking process uses kerosene as the dielectric fluid (Chow et. al., 2007). However there are a lot of dielectric fluids that can be replace to replace kerosene such as pure water (distilled water) because pure water has a high thermal conductivity, a low viscosity coefficient, and a high flowing rate. Pure water temperature is not affected by long working time, and this will improve the material removal rate (MRR).

Recent researches indicated that adding powder in EDM process will enhance MRR, therefore improving the surface roughness, corrosion resistance and wear resistance. Previous researchers (Yan, 1994 and Chen, 1993) used kerosene added with aluminum powder as an EDM dielectric fluid and obtained a high material removal rate and improved surface roughness. Additives can improve the surface quality of workpiece quite effectively by increasing the material removal rate (MRR) and decreasing the tool wear rate especially in mid-finish machining and finish machining (Ming et. al., 1995). But the addition of the powder will have an issue on the relative high cost of the powder addition. Other than that, we can also use oil as the dielectric fluids which will affect the tool electrode wear where it depends on the significance of the pulse duration (Kunieda et. al., 2004)

Recently green manufacturing has become very important to all manufacturing industries because using kerosene will give out pollution that pollutes the air. The use of kerosene has a low ignition temperature with possible conflagration if improper operations are undertaken (Chow, 2007). The use of pure water has more good effect on the workpiece since water has a high thermal conductivity, a low viscosity coefficient, and a high flowing rate and pure water will not be affected by a long working time. Thus a constant high material removal rate will be obtained.

2.5 MINIMUM MACHINABLE SIZE

Recently the demands for microscopic parts have increased and the research on Micro-EDM is becoming more and more important. The minimum machinable diameter of micro rods obtained by EDM is about 5 μm at best. Thus more effort is needed to extend the limits of miniaturization in micro EDM. The factors that affect the limits is maybe because the electric discharge energy of each pulse discharge, this is a result of the discharge crater increases with increasing electric discharge energy (Kawakimi et. al., 2005). However the limits of minimum machinable size are not decided only by the electric discharge energy. Residual stress that is caused by EDM results in distortion of micro workpieces (Spur et. al., 2006).

2.6 PIEZOELECTRIC ACTUATORS (PZT)

Piezoelectric Actuators offers a strong need for compact, robust and efficient positioning mechanism that also offer high precision, short response times, low power consumptions, low magnetic interference and multiple degree of freedom. They can easily be integrated in applications, for example a super amplified actuator for a MRI biomedical device, a chopper for X-ray diffraction, and a tip-tilt for mirrors.

Piezoelectric actuators have been widely used in recent technology applications. A large variety of actuators are commonly available for various applications. These actuators are based on multi-layer ceramics and it can produce large strains at low voltages (Meylan, 2000). They can expand almost proportionally to the applied voltage up to their electric field limit and can typically achieves strains of 0.1% at voltages of 200V (Claeyssen et. al., 2008). Amplified piezoelectric actuators display deformation larger than 1% and strokes of more than 500µm. The linear and rotating piezoelectric motors uses a friction drive mechanism in producing linear displacements up to 100mm and infinite rotation. Actuators offer special advantages to electromagnetic technology in such a way that it gives out high precision machining, a fast response time, and low power consumptions. There are two types of piezo actuators that are discussed which are amplified piezo actuators and super amplified piezo actuators.

2.6.1 Amplified Piezo Actuators

The concept of Amplified Piezoelectric Actuators (APA) according to CedratRecherde relies on the flexural-extensional principles. The concept is where elastic bends under elongation of the piezoelectric actuation. Flexural hinges is not included in the actuator because of its weak characteristics which will be an advantage on low cost. The shell can be used prestress the Ceramic Multilayer Actuator (CMA) and prevent ceramics from working in tensile stress which will lead to an important mass saving. Amplified Piezoelectric Actuators was initially built to help the improvements for micro-positioning optics. This application has generated the largest types of ML and L series as shown in the figure 2.4.

The existence of a range of off-the-shelf actuators is important for developing piezoelectrics mechanism because the development time for the actuator usually not included. Industrial applications also requires passing sever lifetime tests. The APA200M in the figure has passed 10^{10} fast cycles which undergo 200µs rise and fall times of full strokes of 240µm without failure.

Figure 2.4: View of different APA series

Source: Claeyssen et. al. (2008)

2.6.2 Super Amplified Piezo Actuators

Amplified Piezoelectric Actuators can be stacked in series to get a larger stroke because it is compact and centered. This stacking method has been used in a mechanism for a Magnetic Resonance Imaging (MRI). For example three APA200M-NM's is stacked to deliver more than 600µm displacement. In order to increase the actuator stroke to 3mm at 180V with a sub-micron resolution a lever arm is added. The APA is nonmagnetic in order to comply with the MRI environment requirements. The APA shells and the lever arm can be manufactured in a single block to reduce mass and cost because of the planar design.

Figure 2.5: MRI compliant 3mm-stroke mechanism based on three APA200M-NM's. The actuator is actuated at 180V DC and displaying its maximum stroke.

Source: Claeyssen et. al. (2008)

2.7 TYPES OF POWER SUPPLY

In conventional EDM, the current level is high as well as the voltage required. As a result of high currents, the electrode gets locally melted and there is welding of the workpiece and electrode. There are also problems of stray arcing. Moreover, uncontrolled discharge cannot be allowed in micro-machining. Thus a different power supply is required for micro EDM. Pulsed DC power supply is a critical component for achieving the required parameters of accuracy, finish and size of micro holes by using EDM process. The purpose if the power supply is to convert the alternating current into a pulsed unidirectional direct current required to produce the spark and also the effectiveness of the EDM is determined by the type of power supply used.

2.7.1 Rotary Impulse Generator

This is the rotary impulse generator power supply where the voltage waveform is generated based on the DC motor principle, which it creates a sinusoidal wave pattern that is similar to rectification.

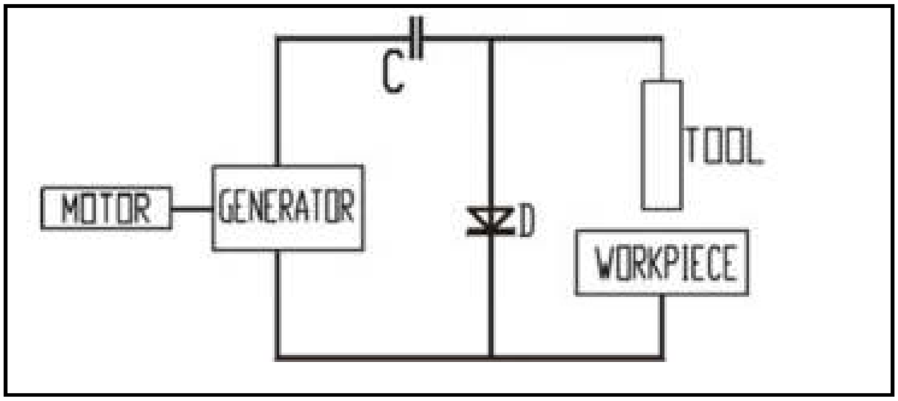


Figure 2.6: Rotary Impulse Generator

Source: Shah et. al. (2007)

2.7.2 Relaxation generator

Figure 2.7 is called the relaxation generator where the principal is based on the charging and discharging of the capacitor that is connected to the power supply. The type of wave that is generated by these arrangements is the saw tooth wave. In creating the spark, the capacitor is allowed to charge and then it is brought to contact with the workpiece and discharges.

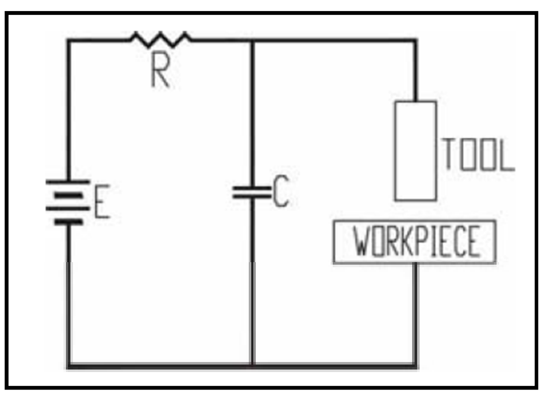


Figure 2.7: Relaxation Generator

Source: Shah et. al. (2007)

2.7.3 Pulse generator

Solid state devices are used instead of capacitor and resistors in pulse generator. Replacing the capacitor a solid-state devices such as the transistor are used. They are toggled between of state and saturation state to generate rectangular pulse which swing between zero and supply voltage. The idea is to increase the production efficiency which it have higher production efficiency than the relaxation circuits.

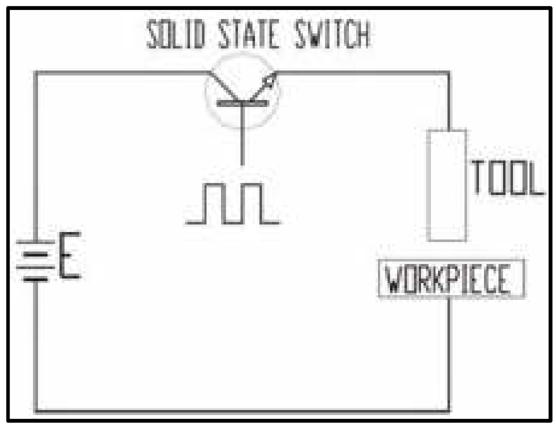


Figure 2.8: Pulse Generator

Source: Shah et. al. (2007)

2.8 EDM PROCESS PARAMETERS

In theory, we can say that the process parameters of EDM and the process parameters of Micro-EDM are quite similar. This is because the working principal is the same which that both of the machining uses Electric Discharge Machining where electrodes discharges pulses and cut away the metal with help of dielectric fluid for better machining accuracy. The dielectric fluid also acts as a lubricant to ensure the machining is accurate and running smooth. We can assume that the process parameters needed in EDM and micro-EDM is similar due to the similarity explained above. It is also states that the micro EDM is similar to the principal of macro EDM where the process mechanism is based on an electro-thermal process that relies on a discharge through a dielectric in order to supply heat to the surface of the work piece (Zarepur et. al., 2007).

2.8.1 Discharge Voltage

The spark gap and the breakdown strength of the dielectric is related to the discharge voltage in EDM processes. Current will flow into the system and before it happen the open gap voltage increases until it has created a path that will go through the dielectric. The path that is mentioned before is called the ionization path. When the current is flowing, voltage drops and stabilizes at the working gap level. The preset voltage determines the width of the spark gap between the leading edge of the electrode and the workpiece (Kumar et. al., 2009). If we set the voltage to a high value then the gap will increase, increasing the gap will improve the flushing conditions and helps to stabilize the cut. The open circuit voltage also have an impact to the system, as we increase the open circuit voltage tool wear rate (TWR) and surface roughness increases because the field strength increases.

2.8.2 Peak Current

Peak current is known as the amount of power used in discharge machining which this parameter is measured in amperage and above all this is the most important parameter in EDM machining. During each on-time pulse, the current increases until it reaches a preset level which is express as the peak current. In roughing operations or cavities in large surface areas higher amperage is used. Using higher currents will definitely improve material removal rate (MRR) but it will give an impact on the surface finish and tool wear. Despite the machine cavity is a replica of tool electrode and excessive wear will hamper the accuracy of machining and as a result, all of the above statements is important in EDM. New improved electrode materials, especially graphite, can work on high currents without much damage (Ho et. al. 2003).

2.8.3 Pulse Duration and Pulse Interval

Expressed in units of microseconds the cycle has an on-time and off –time. On the on-time all the work is produced and as a result the duration of these pulses and the number of cycles per second are important. Metal removal is directly proportional to the amount of energy applied during the on-time (Singh et. al., 2005). The energy applied during the on-time controls the peak amperage and the length of the on-time. Pulse duration and pulse off-time is called pulse interval. If the pulse duration is longer, then more workpiece material will be melted away. Then, it will have a broader and deeper hole than using shorter pulse duration. Even though the hole has rough surface finish, the extended pulse duration will allow more heat sink into the workpiece and in the mean time it will spread which means the recast layer will be larger and the heat affected zone will be deeper.

However, exceeding the pulse duration will also have its benefits. Whereas, when the optimum pulse duration for each electrode and work material combination is exceeded, the material removal rate will start to decrease. The longer the duration will have effect on the wear of the work material where when the duration of the pulse is longer, then there will be a no-wear situation. But there are a certain limits for that point to be reached. But if that point is reached, increasing the duration will cause the electrode to grow from plating build-up. To complete the cycle sufficient pulse interval is needed before the next cycle can be started. Other than that, the pulse interval also affects the speed and the stability of the cut. From theory, the shorter the interval the faster the machining operation will be. But this will affect the workpiece material where it will not be swept away by the flow of the dielectric and as a result the fluid will not be de-ionized. As a result the next pulse will be unstable and hard to control. This unstable condition will cause erratic cycling and retraction of the advancing servo and this will slow down the cutting rate. At the same time, pulse interval must be greater than the de-ionization time to prevent continued sparking at one point (Fuller, 1996). In ideal conditions, each pulse creates a spark. However, it has been observed practically that many pulses fail if duration and interval are not properly set, causing loss of the machining accuracy and those pulses are called open pulses (Kumar et. al., 2009).

2.8.4 Pulse waveform

The normal pulse waveform that we always see is rectangle, but now new shapes have been developed. Pulse wave is a non-sinusoidal waveform that is similar to square wave. By using trapezoidal wave generators the relative tool wear can be reduced to a very low value. Other types of generators introduce an initial pulse of high voltage but low current and a few microseconds duration, before the main pulse, which facilitates ignition (Kumar et. al., 2009).

2.8.5 Polarity

Polarity can be either positive or negative. The current will pass through the gap and create high temperature that will cause the material to evaporate at both the electrode spots. The plasma channel is made of ion and electron flows. Electrons have mass smaller than anions and as the electrons processes it shows quicker reaction, the anode material is worn out predominantly. As a result it causes minimum effect to the tool electrode and becomes important for finishing operations with a shorter on-time. While running long discharges the early electron process predominance changes to positron process which will result in high tool wear rate. Polarity is determined by experiments and is a matter if tool material, work material, current density and pulse length combinations. Modern power supplies insert an opposite polarity "swing pulse" at fixed intervals to prevent arcing (Kumar et. al., 2009). A typical ratio is 1 swing for every 15 standard pulses (Ho et. al., 2003).

2.8.6 Electrode Gap

The tool servo-mechanism is one of the most important in the efficient working of EDM process, and the servo-mechanism function is to control the working gap to the set value. An electro-mechanical and hydraulic systems are used and normally designed to respond to average gap voltage. In order to obtain good performance, gap stability and the reaction speed of the system needs to be account for where the presence of backlash is particularly undesirable. For the reaction speed, it must obtain a high speed so that it can respond to short circuits or even open gap circuits. Gap width is not measured directly, but can be inferred from the average gap voltage (Crookall et. al., 1971)

2.8.7 Type of Dielectric Flushing

A dielectric in EDM must have a basic characteristic of high dielectric strength and quick recoveries after breakdown also have an effective quenching and flushing ability. Tool wear rate and material removal rate is affected by the type of dielectric used and the method of its flushing. The use of hydrocarbon compounds and water are commonly used as dielectric fluids. But for de-ionized water is usually used for wire-EDM and high precision die-sinking because of its low viscosity and carbon free characteristics. The dielectric fluid is flushed through the spark gap to remove gaseous and solid debris during machining in order to maintain the temperature so that it is always below the flash point. A control feature that is commonly seen on many machines to facilitate chip removal is vibration or cyclic reciprocation of the servo tool electrode to create a hydraulic pumping action. Orbiting of the tool workpiece has also been found to assist flushing and improve machining conditions (Levy et.al., 1975).

2.9 TOOL WEAR RATE (TWR)

The ratio of amount of electrode to the amount of workpiece removal is defined as the wear ratio (Tsai et. al., 2004). There are four methods that are known to evaluate the electrode wear ratio by means of measuring weight, shape, length, and total volume respectively. A common one is by calculating the volumetric wear ratio (υ). Usually we will measure the weight differences and transfer them into the volumes by the density of materials. However this method is unsuitable for micro-EDM because the weight change is so small making it difficult to measure it accurately. Therefore, it is important to measure and analyze removed material directly.

In figure 2.9 the change of electrode length and corner rounding is illustrated. In the figure the worn electrode can be divided into two parts which is $V_B$and $V_{C.}$ V_C is the wear volume on bottom portion and V_C is the wear volumes of corner portion and $V_C$are assumed to be the volume of a cylinder of a revolution body, respectively, because a rotating electrode is used during machining.

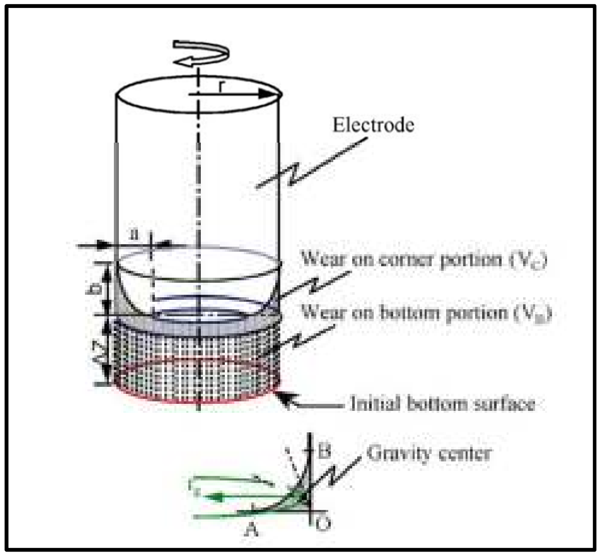


Figure 2.9: Wear volume of the electrode

Source: Tsai et. al. (2004)

2.10 MATERIAL REMOVAL RATE (MRR)

The source energy of electro discharge between the tool electrode and the workpiece is an electric one which power can be determined by the supplied voltage and current. Thus, the electro discharge energy can be expressed as shown in Eq. (2.1).

$$E = VIT \tag{2.1}$$

In the pulse current, if time T is substituted to an intermittent one with frequency, Eq. (2.2) is expressed to the following

$$E_p = V_p I_p t_{on} \frac{1}{t_{on} + t_{off}} \tag{2.2}$$

Where;

Symbols	
V_p	Voltage of a single pulse
I_p	Current of a single pulse
t_{on}	pulse on-time
t_{off}	pulse off-time

The equation for material removal rate can be produce by multiplication of machining property. Hence the expression can be written as Eq. (2.3):

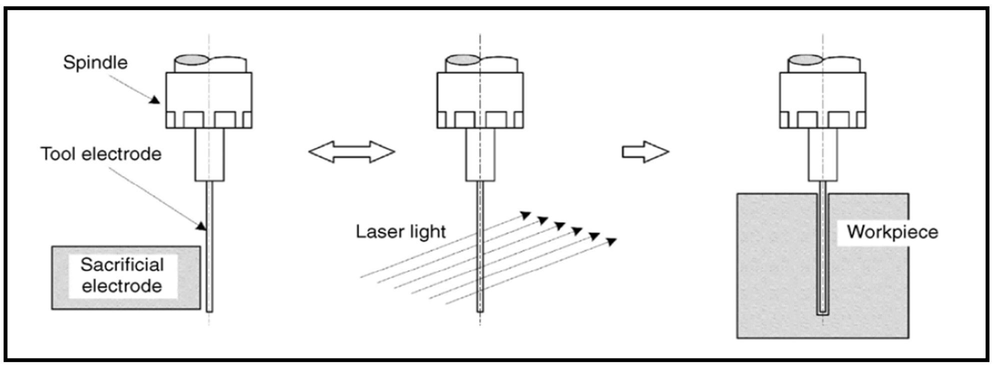
$$MRR = \alpha V_p I_p t_{on} \frac{1}{t_{on} + t_{off}} \tag{2.3}$$

Where α is the removal constant of a material. This constant is the removal volume of a material per unit electric power.

From Eq. (2.3) the parameters of voltage, current and pulse On-time are proportional to the material removal rate. At the same time the frequency of the pulse is also proportional to the material removal rate, but the parameter is not perfectly independent of the pulse On-time. This is because the pulse Off-time is needed sufficiently, depending on the power of a single pulse. The equation also indicates that a shorter duration is more advantageous than a longer one to make accurate machining under the same conditions. 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.

2.11 HIGH ASPECT RATIO OF MICRO-FABRICATION USING MICRO-EDM

Micro-EDM is a non-traditional machining technology that has been found to be the most efficient for fabricating micro-components (Rahman et. al., 2007). This method is a contactless method where the electrode discharges pulses on the workpiece and it is capable of machining ductile, brittle and super-hardened material. Micro-EDM can achieve high precision machining and increases the quality if the appropriate parameters are used. It is possible to use long and thin electrode for the machining since it is a non-contact process. Micro-EDM has disadvantages of high electrode wear ratio and low material removal rate. The wear of the electrode must be compensated by changing the electrode or by preparing longer electrode from the beginning or fabricating the electrode in situ for further machining. It is not recommended to change the electrode during machining because it can reduce the accuracy due to the change in setup or re-clamping of the micro-electrode. Below shown is the conceptual process to fabricate high aspect ratio microstructures using micro-EDM.



a) On machine tool fabrication by micro-EDM

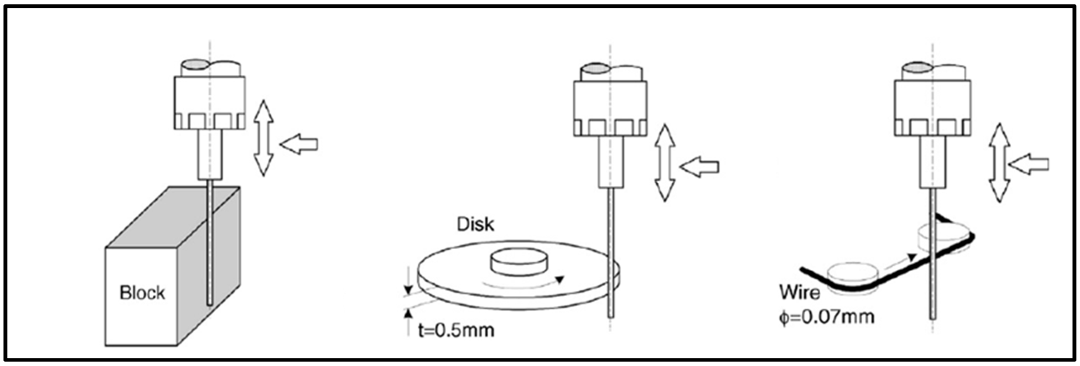
b) On machine optical measurement

c) Fabrication of high aspect ratio micro structure by micro EDM

Figure 2.10: Process to fabricate high aspect ratio microstructures using micro EDM

Source: Rahman et. al. (2007)

In micro-EDM process, the tool electrode is fabricated on the machine to avoid clamping error. The electrode is fabricated to be thicker than the required diameter, and a cylindrical electrode is fabricated by EDM process using a sacrificial electrode. Different setup can be used in this process. From figure 2.10, figure.2.10 (a), when there is a dimensional change in the sacrificial electrode then the diameter of the tool electrode fabricated by the process is usually unpredictable. To counter that problem an on-machine measurement needs to be conducted for the tool electrode to make sure that the desired diameter is obtained. From figure 2.10 (b), developing a special optical measuring device to measure the thin electrode, which consists of a laser diode, optical filter and photo detectors. After measuring the diameter a compensated machining schedule for the tool electrode fabrication is generated and then the machining will be carried out. After the tool electrode fabrication is finished, micro-EDM is performed to fabricate the high aspect ratio microstructures which can be seen in figure 2.10 (c).



a) stationary sacrificial block
b) Rotating sacrificial disk
c) Guiding running wire

Figure 2.11: Three types of sacrificial electrode for on-machine tool fabrication

Source: Rahman et. al. (2007)

The figure above shows the types of sacrificial electrode for on-machine fabrication. From figure 2.11 (a), shows a stationary block, which is said to be the simplest method to machine a tool electrode. From figure 2.11 (b), shows a rotating disk with a diameter of 60 mm and thickness of 5 mm. During the tool fabrication the rotating disk is set to approximately 90 rpm. AS can be seen in figure 2.11 (c), shows a guided running wire as a sacrificial electrode of 0.07 mm in diameter. The speed of the wire is about 3-5 mm/s. This method is also known as wire electro-discharge grinding (WEDG), and it is a typical method in micro-EDM. The spindle is moving at 300 rpm and it moves up and down according to the tool electrode contact condition during the tool fabrication process. This means that the spindle is under control to maintain the

EDM spark gap. Once the tool reaches one end of its stroke movement, the tool moves forward the electrode to a given depth of cut, and the process is continuously repeated.

2.12 SERVO FEED CONTROL SYSTEM

In order to keep the gap distant constant, adaptive servo feed control is used in conventional EDM where the average working voltage is monitored and the electrode feed rate is controlled to keep the average working voltage in the gap constant (Shinya et.al., 2007). The gap distant in micro-EDM is much shorter than that in conventional EDM due to the small pulse energy; micro-EDM machining tends to become unstable and it is suggested that the use of adaptive servo control is more essential for micro-EDM.

2.13 5 DEGREE OF FREEDOM (DOF) CONTROLLED MAGLEV LOCAL ACTUATOR

Electrical Discharge Machining has the capability to machine all kinds of conductive materials regardless of hardness and EDM also has the ability to machined complex shapes. But the speed and accuracy of EDM are limited by the probability and efficiency of the electric discharges. In order to obtain a stable electrical discharge, the electrode needs to be speedily re-positioned in order to maintain a suitable distance from the workpiece, and the debris around the electrode due to the EDM has to be removed immediately (Zhang, 2008).

To position the electrode in three orthogonal directions, stacked one-DOF lead screws are normally used in conventional discharge machines that can be seen in Fig. 10. Although the stroke of the lead screw positioning mechanism is adequate, the positioning response is somewhat slow to allow a suitable discharge distance to be maintained due to the mass of stacked tables and the rotary inertia of the lead screw.

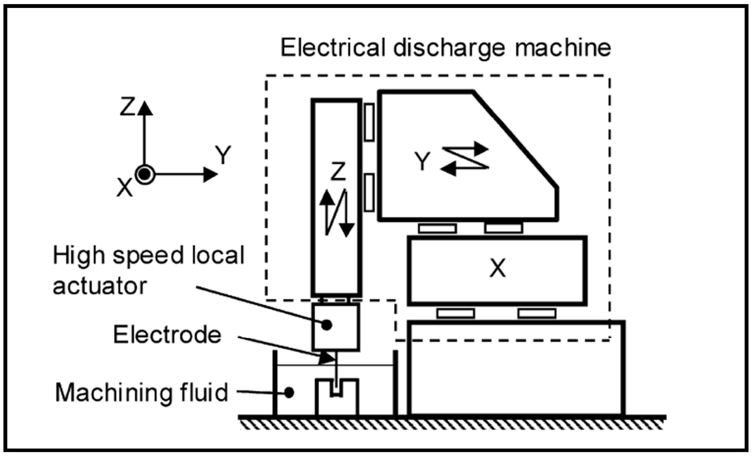


Figure 2.12: Electrical Discharge Machining with an additional local actuator

Source: Zhang (2008)

The main purpose is to improve the positioning accuracy whereas a combination of a conventional electrical discharge machine and a wide-bandwidth, high precision, multi-DOF is required, that can be seen in Fig. 2.12. As for the local actuator, a positioning stroke ranging of a few millimeters for rapid retraction of the electrode in at least on direction of motion is necessary, in order to remove debris from around the electrode when holes with high aspect ratio is machined. By adding the local piezoelectric actuator it will be used to improve the positioning response of electrodes. However, to realize motion in 5-DOF using piezoelectric elements, a complex elastic hinge mechanism, occupying a large space, is required. In addition, the stroke of the piezoelectric actuator is insufficient for periodic rapid retraction of the electrode. Then after, we have to use fresh machining fluid to wash away the debris from the machined hole.

2.14 MICRO-EDM ISSUES AND ERRORS

This section is based on the facts of Micro-EDM issues and errors that have been detected by previous researchers. Based on these statements, the figure below shows the problematic areas of Micro-EDM processes. From the figure we can see the problematic areas which is handling, electrode and workpiece preparation, machining processes, and measurement.

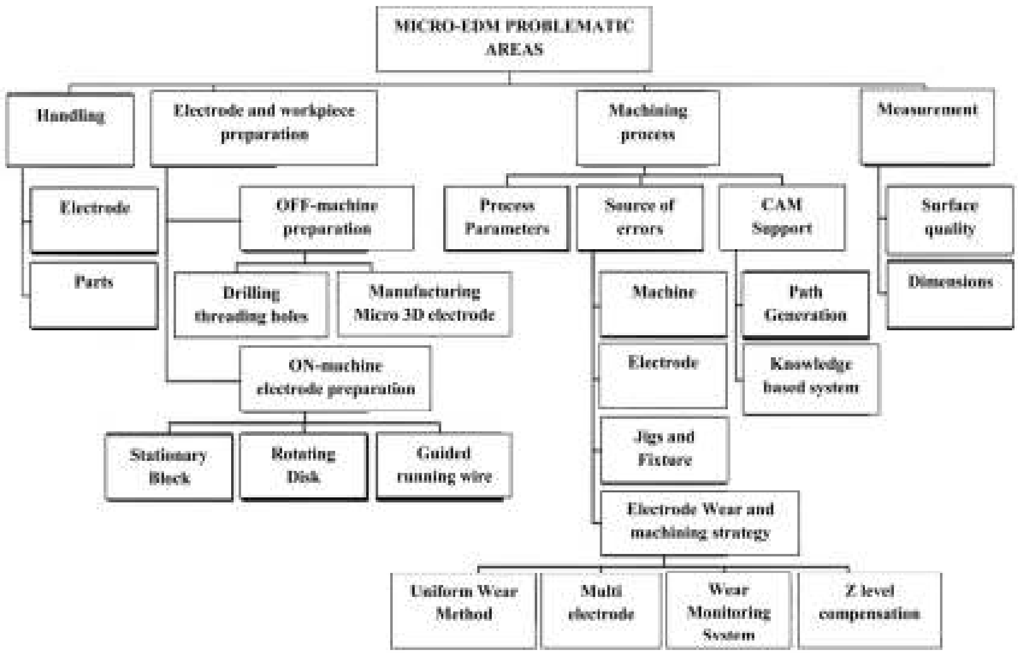


Figure 2.13: Problematic areas in Micro-EDM

Source: Pham (2004)

2.14.1 Handling of Electrodes and Parts

Recent studies indicate that to reduce the diameter if the wire used in wire EDM has caused many problems with handling electrodes and parts. Initially, existing wire machines were adapted to take smaller diameter wires down to 0.03 mm. However this will demand a significant time for preparing the machine. The distance of the spool position to the threading nozzle was long, and caused a great deal of inconvenience for the installation of the wire. However the dynamic force on the brakes could not be taken easily by the very thin wire. In conjunction to that there are frequent wire breaks which require manual intervention. Newly developed wire-EDM machines also have problems in manipulating and handling wires with diameter as small as 0.02 mm – 0.03 mm. When micro parts are produced in wire machine the handling of the parts can also be challenging. A special measure should be considered after a separation cut to avoid losing parts into the tank of the machine (Pham, 2004).

In micro EDM die-sinking, drilling, or milling, different techniques and devices can be used to help handling and manipulating small electrodes and parts. The electrode that are mainly used for EDM drilling and milling are tungsten (W) or tungsten carbide (WC) rods or tubes of diameter ranging from 0.1-0.4mm, plus their handling is difficult whereas they can be easily damaged. Thus the subsystems are incorporated into micro-EDM machines for on-the-machine manufacture. Ceramic guides and dressing units such as wire electro-discharge grinders are the most common sub-systems.

2.14.2 Electrode and Workpiece Preparation

In micro-wire EDM, practically the main issue in workpiece preparation relate to the production of small holes used for threading the wire into the workpiece. These holes can have micro-diameters with a high aspect ratio depending on the profile of the machined product with respect to the measuring point the accuracy of positioning the hole should be high. This is because so that the automatic threading procedure will be at ease and it can also avoid short-circuiting after the threading process, even though automatic threading of such holes even using specialized micro-wire machines is difficult. When die sinking of micro-features is required, one or more electrodes are produced in advance usually either by micro-milling or by EDM. According to this case the micro-features are machined onto the electrode should be offset with the spark gap. Thus, the feature size is diminished which causes distortion of the form, where making the geometry is partially impossible (Pham, 2004). Production of such 3D profile is costly and time consuming as well. EDM milling uses a simple shaped electrode, rod or tube of diameter between 0.1 and 0.4 mm. The electrode can be EDM ground if a smaller diameter is required. In order to avoid handling difficulties and error stack-up when the electrode is manufactured externally, additional devices are used to prepare the electrode on the machine. The working electrode is eroded against a sacrificial electrode in an operation known as EDM grinding. As you can see in Fig. 9 the three different types of sacrificial electrodes used (Pham, 2004). The problem is, the shape, dimension and roughness of the ground electrode is shard to control.

2.14.3 EDM Process

The process planning for Micro-EDM should be considered very carefully, as feature sizes are very small and so are the tolerances of the machined surface. During the preparation stage and the machining process itself, a number of errors occurs which may lead to a disappointing result. Due to the equipment imperfection on the hand and the stochastic nature of the sparking process on the other these errors occur (Ho, 2003).

Recent studies have target ways to optimize EDM performance measures like materials removal rate (MRR) which has been discussed earlier, tool wear rate (TWR) and surface quality. Since process parameters for micro-EDM are still on the development stage and their effect on performance have yet to be clarified. It is difficult to explain the effects fully because of the stochastic thermal nature of the process. The optimization of the parameters is mainly based on the analysis to reveal the influence of each process variable on the desired machining characteristic. The main reason for the inability of developing knowledge-based system to help the planning process of micro-EDM is due to the lacks of information.

Even though we have used CNC controllers and the high degree of automation of EDM machines, there is still lack of CAM tools to support micro-EDM. One of the main reasons for the limited application of micro-EDM milling to the machining complex of 3D cavities is the difficulty of generating tool paths using existing CAM systems. Predominantly, those systems do not allow electrode wear compensation, nor support variation of the slice thickness to allow the direction of cut to vary with each slice. The attempts to address these issues have been reported (Ho, 2003).

2.14.4 Measurement

To measure the dimensions and surface quality of micro-features is difficult. This is because there are no standardize methods of determining the surface roughness where as we all know that the surface roughness is one of the most important characteristic for micro-tooling. To estimate the recast layer and the heat affected zone which gives effect to the machined surface requires specialized equipment which is costly. In order to achieve good accuracy in micro-EDM on-the-machine measurement of electrode and feature dimensions is advisable (necessary). This is because after a part has been taken out of the machine for measurement is reinstated for more machining; the resetting error will drastically affect the final accuracy of the machined features. As for the work on-line feature and electrode measurement has been already reported.

2.15 SOURCE OF ERRORS IN MICRO-EDM

Previous research uses a single pass drilling of a small hole using a dressed electrode as an example to describe the typical sources of errors and their cumulative effect on the final accuracy. The achieved diameter H of the hole depends on the diameter of the effective dressed electrode diameter d and the spark gap g_e.As shown in figure 2.14.

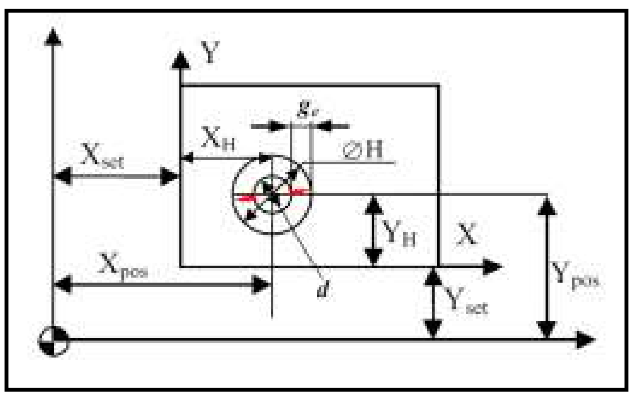


Figure 2.14: Achieved Diameter

Source: Pham (2004)

$$H = 2g_e + d \tag{2.4}$$

$$\Delta H = 2\Delta g_e + \Delta d \tag{2.5}$$

The equation shows the deviation from the normal H(ΔH) is function of variations in the spark gap Δg_e and the effective dressed electrode diameter Δd. The position of the hole is given by the following equation that is derived from figure 2.14.

$$X_h = X_{pos} - X_{set}, \qquad Y_h = Y_{pos} - Y_{set} \tag{2.6}$$

To setup the workpiece in the work area, the machine spindle which is an electrode of nominal effective diameter (D) is employed as a probe. Should be noted that the used of external probes or other setup devices is ruled out because it would require reattachment of the high-speed spindle and readjusting of the ceramic guide therefore it will introduces more errors. The setup process is illustrated in figure 2.15.

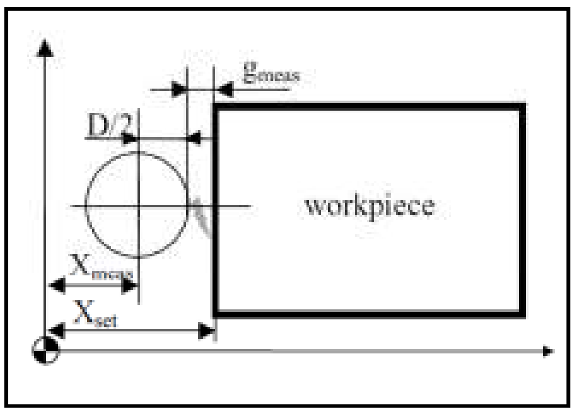


Figure 2.15: Setting up process

Source: Pham (2004)

$$X_H = X_{pos} - (X_{meas} + g_{meas} + \frac{1}{2}D) \tag{2.7}$$

$$Y_H = Y_{pos} - (Y_{meas} + g_{meas} + \frac{1}{2}D) \tag{2.8}$$

The deviations are respectively:

$$\Delta X_H = \Delta X_{pos} + \Delta X_{meas} + \Delta g_{meas} + \frac{1}{2}\Delta D \quad (2.9)$$

$$\Delta Y_H = \Delta Y_{pos} + \Delta Y_{meas} + \Delta g_{meas} + \frac{1}{2}\Delta D \quad (2.10)$$

The accuracy of the position of the hole will depend on the accuracy of positioning of the machine (ΔX_{pos} ,ΔY_{pos}) accuracy of detecting contact with the surface (Δg_{meas},$\Delta Y_{meas}\Delta X_{meas}$) and the variation in the initial effective diameter (ΔD)

2.15.1 Machine errors

2.15.1.1 Accuracy and Repeatability of Positioning

The accuracy and repeatability of positioning of the machine employed is a major cause or errors. Previous research proves that using a laser interferometer, the accuracy and repeatability of a micro-EDM die sinking machine was measured to ISO 230-2:1997 and some results have been given in Table 2.1.

Table 2.1: Repeatability and accuracy of positioning

	Repeatability of positioning			**Accuracy of positioning**		
	X(μm)	**Y(μm)**	**Z(μm)**	**X(μm)**	**Y(μm)**	**Z(μm)**
unidirectional↑	3.76	4.49	1.48	14.03	5.03	2.39
unidirectional↓	2.95	4.92	1.27	11.85	5.18	1.82
Bi-directional	5.33	7.83	1.90	15.70	7.91	2.73

Adapted from: Pham (2004)

In order to machine a micro-hole at a specific position, a multiple dress electrodes might be required and therefore the accuracy of positioning of the machine will mainly effect the position of the hole, while the repeatability of positioning will impact on the size and shape of the hole. It is different on different machines where with a certain accuracy and repeatability if positioning, the only way to improve $\Delta X_{pos}$and ΔY_{pos} is to adopt a unidirectional approach to the hole.

2.15.1.2 Measuring Cycles Errors (ΔD,$\Delta \mathbf{Y_{meas}} \Delta \mathbf{X_{meas}}$)

During the setting up of the workpiece, and when the electrical contact occurs between the electrode and the workpiece, a contact signal is registered by the machine system processor. The processor has been set to priorities to check on each machine status signal, which means that the checking of the contact signal is not carried out continuously. There is also a time interval between each signal. This causes an error in determining the position of the workpiece when measuring X_{meas} and Y_{meas}. Let say the speed approaching the surface is V_{meas}, the variation will be:

$$\Delta \mathrm{X_{meas}} \, (\Delta \mathrm{Y_{meas}}) = \mathrm{V_{meas}} \, \mathrm{t_{meas}} \qquad (2.11)$$

The contact signal is checked every 2-5ms depending on the controller. In order to minimize the error the speed should be as low as possible but high enough to avoid stick-slip. For example, if t_{meas} is 3 ms and the measuring speed is from 1 to 20mm/min, the calculated variation is 0.05-1µm. During the measuring cycle, voltage is applied between the table and the spindle. The machine moves until electrical contact is made. As the surfaces tend to oxidize a different gap or different contact pressure is needed for the spark to break through. All these factors contribute to a surface detection error introducing variation in the spark gap Δg_{meas}.

$\Delta D$is due to the cyclic movement of the electrode in X and Y within the ceramic guide while the electrode is rotating. Therefore, the contact between the electrode and the surface might occur at different positions in the cycle. The accuracy of the measurement is dependent on the speed of the approach to the workpiece surface. The lower it is in relation to the speed of rotation of the electrode, the smaller the error will be. This has been confirmed by an experiment done by previous researchers which the variations in surface detection on a WC block with a diameter of 150µm WC electrode at different approach speeds were measured. For speeds of 20, 5, and 1 mm/min which is the lowest speed of the machine, $\Delta g_{meas} + \Delta\frac{D}{2}$ is respectively equal to 5.7, 3.9 and 3μm.

2.15.2 Electrode Dressing

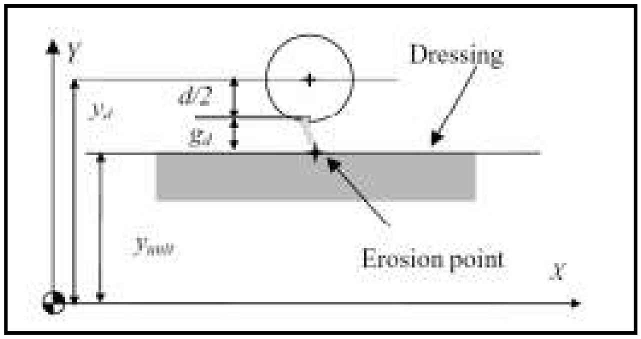


Figure 2.16: Dressing process

Source: Pham (2004)

In order to reduce the initial effective diameter D down to an effective diameter d, an electrical-discharge grinding unit is employed as shown in Fig. 14. Movement in the dressing process is performed along the Y axis. The distancey_{unit}gives the position of the eroding point in the work area of the machine relative to the machine reference point. Until the centre of the spindle reaches a target position y_d where the electrode is eroded, the result will give an effective dressed electrode of diameter d. Taking into account the spark gap g_d between the electrode and the dressing unit, the obtained effective diameter d is define equation:

$$d = 2(y_d - y_{unit} - g_d) \quad (2.12)$$

The variation in d(Δd) will depend on the variation in the position of the grinding device Δy_{unit}. The variation in the positioning of the centre of thee electrode $\Delta y_d$and the variation of the spark gap when grindingΔg_d.

$$\Delta d = 2(\Delta y_d + \Delta y_{unit} + \Delta g_d) \quad (2.13)$$

Finally, the variation in the diameter of the hole drilled by a single dressed will be determined by:

$$H = 2(g_e + y_d - y_{unit} - \Delta g_d) \quad (2.14)$$

$$\Delta H = 2(\Delta g_e + \Delta y_d + \Delta y_{unit} + \Delta g_d) \quad (2.15)$$

The variation Δy_d will arise due to the machine accuracy and repeatability of positioning. A way to reduce Δy_d during the dressing process is to approach the position from the same direction (unidirectional approach). Other ways to limit the error is to identify an area on-the-machine and fix the dressing unit where the repeatability of positioning is the highest.

2.15.2.1 Temperature Instability Error

$y_{unit}$is the position of the point of erosion on the dressing unit in the machine co-ordinate system. Changes in the temperature in the room and in the machine structure causes variations in the relative position between the rotating head and the table of the machine and therefore affect the position of the dressing unit with respect to the electrode and the machine zero point (Pham, 2004). A way to minimize those variations is to work in a temperature-controlled room to ensure thermal stability of the machine structure. Each machine should be tested to establish the time for the temperature of the machine to stabilize for certain ambient conditions and the temperature-related deviation of each axis should be measured in order to plan electrode dressing with minimum error.

2.15.2.2 Spark Gaps Δg_e , Δg_d

The gap between the electrode and the workpiece is defined as g_e. Its nominal value is determined by the chosen pulse parameter (shape, length and frequency) and the dielectric used. In conventional EDM, the selection of pulse parameters is directly linked with the removal rate and surface roughness required. In micro-EDM, electrode wear is another important criterion which also needs to be carefully considered. The spark should be very small in order to achieve micro-EDM features. Variations in $g_e(\Delta g_e)$ bring random errors which can occur due to flushing conditions and lack of surface/material integrity. $g_d$is defined as the gap between the electrode and the dressing unit. In the case of $g_e$the value of $g_d$is fixed by the chosen pulse parameters and dielectric material, and variations in $g_d(\Delta g_d)$ can arise due flushing conditions and lack of surface/material integrity (Lim, 2003). The pulse parameters are selected depending on the surface roughness required and on the speed of dressing. Since the electrode is rotating, its surface roughness should not significantly influence the roughness of the machined surfaces. However, due to the small dimensions involved, a high degree of roughness will affect the strength of the dressed electrodes' which could break during the process. Estimation of Δg_d is difficult but it can be assumed that it will not exceed Δg_ein the worst case. During dressing, sparking condition are more favorable than during drilling itself as dressing involves single point sparking with better flushing.

2.16 Jigs and Fixtures

The most popular device for holding the ling thin WC electrode is a ceramic guide. The effective diameter of the electrode D is determined by the initial diameter $D_{initial}$ and the assembly conditions between the electrode and the ceramic guide. The difference between the diameter $D_{initial}$ and the diameter of the ceramic guide D_{guide}creates a gap that introduces potential errors as shown in figure below (Pham, 2004).

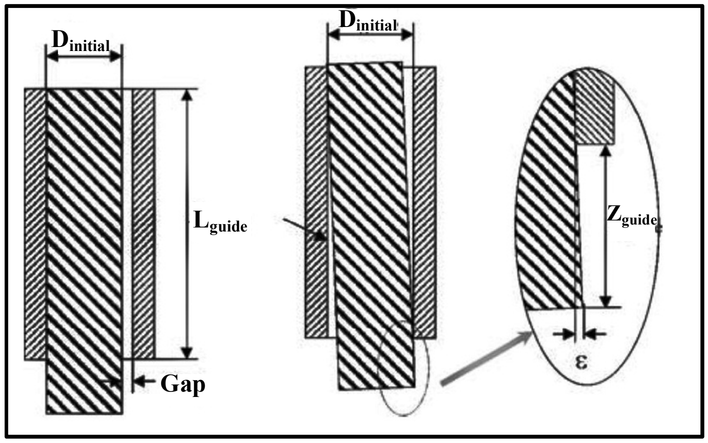


Figure 2.17: Effect of gap between ceramic guide and electrode

Source: Pham (2004)

Thus variations in the effective diameter ΔD can occur which reflect the tolerance of the electrode and the assembly conditions between the electrode and the ceramic guide. Based on the figure, the maximum variation in effective electrode diameter is defined by,

$$\Delta D = D_{guide} + \frac{(D_{guide} - D_{init\_min})z_{guide}}{L_{guide}} - D_{init\_min} \tag{2.16}$$

In above equation, D_{guide} is the diameter of the guide, $D_{init_min}$is the minimum diameter of the initial electrode according to the manufactured tolerance and $z_{guide}$is the length of the electrode protruding from the ceramic guide. Previous researchers have experiment on the above problems and come up with, the diameter of the electrode:

$$D_{init} = 0.146 \pm 0.002\text{mm}$$

$$D_{init\_min} = 0.144\text{mm}$$

The measured diameter of the ceramic guide was,

$$D_{guide} = 0.154\text{mm}$$

$L_{guide}$was 12 mm, and $z_{guide}$was less than 2mm. Based on those values the calculated maximum deviation ΔD was 13.3 μm. However, this maximum variation can only occur when the position of the electrode within the guide shifts to a number of extreme points. This is only possible when there is significant movement of the electrode along the X and Y axes that is relative to the guide.

2.17 Electrode wear

Electrode wear is not a major problem for micro-wire EDM, apart from the fact that a high rate of wear might cause more frequent wire breaks. This is due to the fact that wear reduces the cross section of the micro-wire and therefore the maximum tension the wire can take drops significantly. Electrode wear becomes an important issue when employing electrodes with micro-features in die-sinking as the combination of micro-features and macro-features on one electrode will introduce different wear ratios. The sparking area will change as the electrode moves down, which will bring different sparking conditions during the process and will reduce quality. In micro-EDM drilling, there are problems when producing blind holes because wear constantly reduces the length of the electrode. As a result, when eroding down to a fixed depth, the real depth of the hole will be significantly smaller. A method to achieve a specific depth in this case is to compensate for wear of the electrode by constant electrode feeding in the *Z*-axis (Bleys et. al., 2002)

This method requires an accurate model for estimating the volumetric wear ratio (the ratio of electrode wear and workpiece wear). Certain factors affecting the wear ratio are difficult to assess and control, like flushing conditions in a deep hole for instance. This could easily result in wrong estimation of the wear ratio and therefore in errors in the produced depth. The shape of the electrode also changes during machining (Fig. 2.18) towards a hemisphere, which causes errors in the produced bottom surface. 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-shape electrodes in a classical die-sinking process or electrode geometry is impossible.

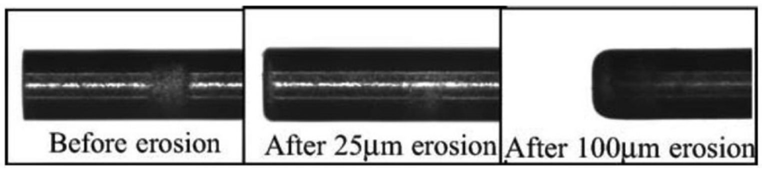


Figure 2.18: Electrode shape changes on a diameter 150μm electrode for two erosion depths.

Source: Pham (2004)

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. In the uniform wear method (UWM) (Yu. et. al., 1998) the tool electrode is specially designed to ensure that after the machining of each layer the original shape of the electrode is restored. This is done using a combination of carefully designed overlapping tool paths and very small layer thickness (0.5–10μm). The use of thin layers results in good flushing conditions, a more stable erosion process and therefore more predictable wear. UWM involves a time consuming empirical approach for selecting tool paths (Yu et. al., 1998). The design of these tool paths derives from the values of the cross section area of the electrode, the area of the layer surface, the depth of cut and the volumetric wear ratio which are assumed to be constant. Any variation in one of these values could introduce discrepancies in the machined layer, and would affect the values of the parameters for the next layers.

As the sparking conditions and therefore the volumetric wear might not be constant during the erosion process, another type of compensation method has been proposed, which is based on the monitoring of the sparking conditions during the process in order to estimate wear on-line using a mathematical model of the sparking efficiency. Such a method has been considered for conventional EDM (Bleys et. al., 2002 and Dauw et. al., 1986), However, because of the accuracy required, its development in micro-EDM is still at an early stage. A sufficiently accurate mathematical model representing the sparking phenomenon is yet to be found.

The main problem with previously presented wear compensation methods 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. Many researchers have focused on the difficult problem of wear estimation (Yu et. al., 2003) but the accuracy of the proposed models still needs to be verified for use in micro-EDM milling. In this paper, a simple method based on the multiple electrode strategy is proposed, which can give a better level of repeatability and accuracy for micro-EDM milling. One of the main advantages is a significantly reduced risk of overcutting the profiles.

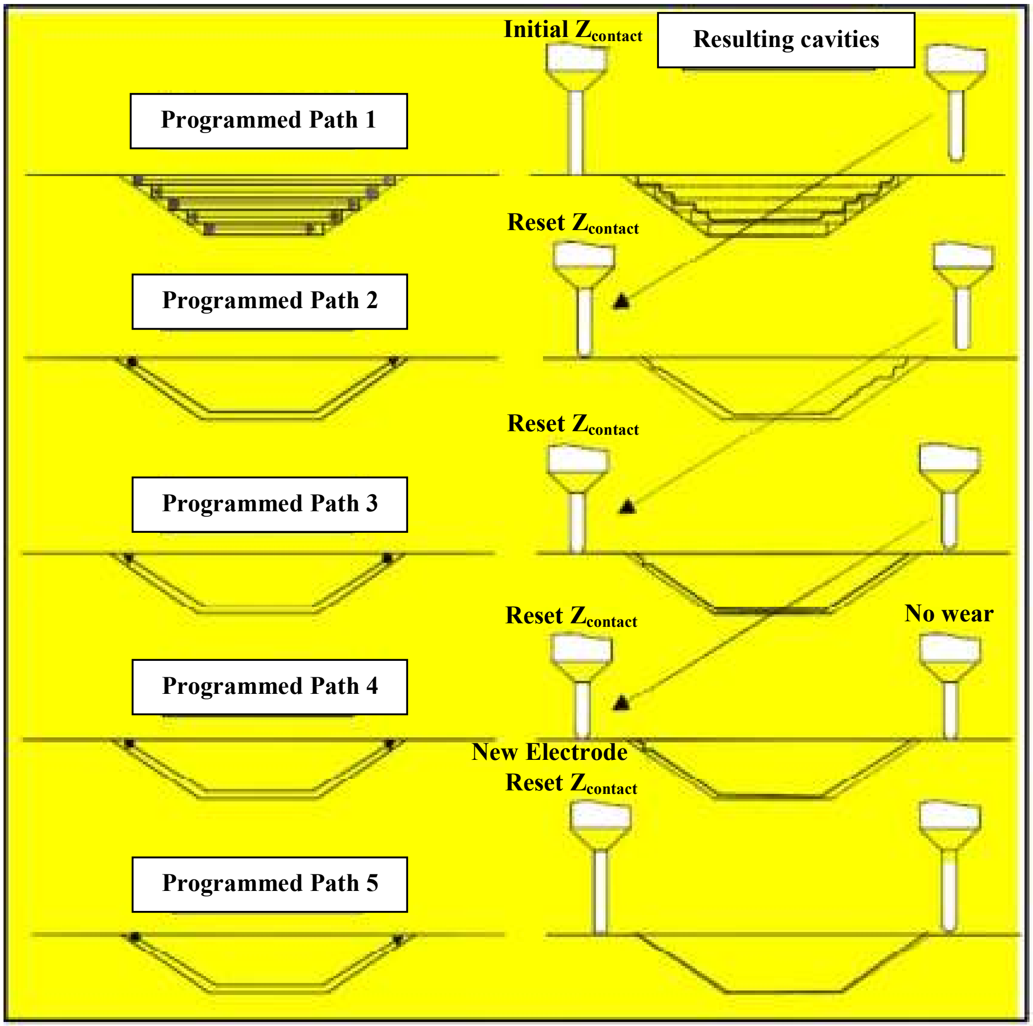


Figure 2.19: Proposed strategy for wear compensation

Source: Pham (2004)

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 Zcontact 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. To illustrate the process, an example is given in Fig. 2.18. After the first machining pass (Path 1 in Fig. 2.18), 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. 2.18), 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. 2.18). 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 of material. In order to estimate the number of passes required, an estimation model similar to the one presented in reference (Meeusen et. al., 2002) could be used. With improvements in wear estimation models, further developments in compensation methods may be expected. They are likely to focus on hybrid compensation approaches, where for instance UWM could be first used, ensuring no overcutting, and then a multiple electrode strategy would accurately finish the profile. The accuracy and reliability of accurately finish the profile. The accuracy and reliability of be applied industrially.

2.18 OPEN FLOW CHANNELS IN DIELECTRIC FLUSHING CIRCULATION SYSTEM

Open flow channels refers to the flow of liquids in channels open to the atmosphere or in partially filled conduits and is characterized by the presence of a liquid gas interface called the free surface. The dielectric circulation system can be referred as an open channel flow. In symmetric open channel, the flow velocity is zero at the side and bottom surfaces because of the no-slip condition, and the maximum midplane of the free surface. The secondary flows, as in the bends of noncircular channels, the maximum velocity occurs below the free surface somewhere within the top 25 percent of depth (Cengal, 2006). Therefore, the velocity distribution in open channel is, in general, three dimensional. Open channel flows are also classified as being steady or unsteady. A flow is said to be steady if there is no change with time at a given location. The representative quantity in open channel flow is the flow depth (average velocity), which may vary along the channel. The flow is said to be steady if the flow depth does not vary with time at any given location along the channel. Otherwise, the flow is unsteady.

2.18.1 Uniform and Varied Flows

Flow in open channel is also classified as being uniform or non-uniform, depending on how the flow depth *y* (the distance of the free surface from the bottom of the channel measured in the vertical direction) varies along the channel. The flow in a channel is said to be uniform if the flow depth remains constant. Otherwise, the flow is said to be non-uniform or varied, indicating that the flow depth varies with the distance in the flow direction.

In open channels of constant slope and constant cross section, the liquid accelerates until the head loss due to frictional effects equals to the elevation drops. The liquid at this point reaches its terminal velocity and uniform flow is established. The flow remains uniform as long as the slope, cross section, uniform flow is called the normal depth $y_n$which is an important characteristic parameter for open channel flows.

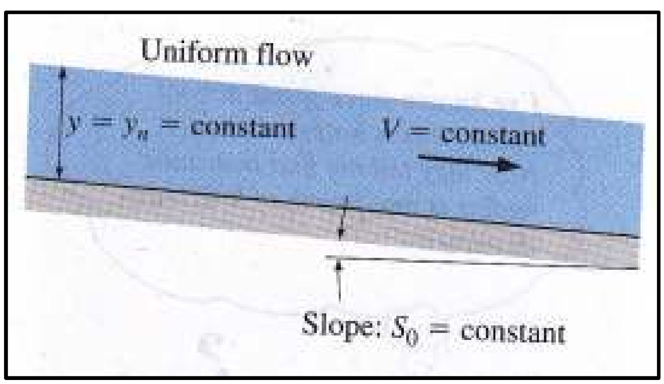


Figure 2.20: For uniform flow in an open channel, the flow depth y and the average flow velocity V remain constant

Source: Cengel (2006)

The presence of an obstruction in the channel, such as the gate or a change in slope or cross section, causes the flow depth to vary, and thus the flow to become varied or non-uniform. These types of varied flow are common in both natural and human-made open channels such as river, irrigation systems and sewer lines.

2.18.2 Laminar and Turbulent Flows in Channel

Like pipe flow, open channel flow can be laminar, transitional or turbulent, depending on the value of the Reynolds number expressed as;

$$\mathrm{Re} = \frac{\rho V R_h}{\mu} \tag{2.17}$$

Here V is the average the liquid velocity, v is the kinematic viscosity, and R_h is the hydraulics radius defined as the ratio of the cross-sectional flow area $A_c$and the wetted perimeter p;

$$R_h = \frac{A_c}{p} \tag{2.18}$$

Considering that open channels come with rather irregular cross sections, the hydraulics radius serves as the characteristic dimension and bring formity to the treatment of open channels. Then the relation between hydraulic radius and hydraulic diameter,

$$D_h = \frac{4A_c}{p} = 4R_h \tag{2.19}$$

So from the equation, the hydraulic radius is one-fourth of the hydraulic diameter. Therefore a Reynolds number based on the hydraulic radius is one-fourth if the Reynolds number based on the hydraulic diameter as the characteristic dimension.

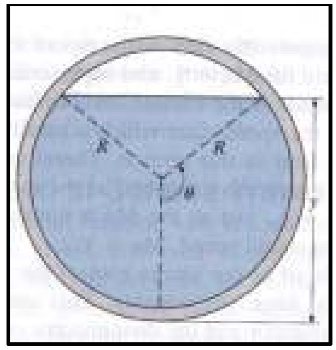


Figure 2.21: Circular Channel (θ in rad)

Adapted from: Cengel (2006)

$$A_c = R^2(\theta - \sin\theta\cos\theta) \quad (2.20)$$

$$p = 2R\theta \quad (2.21)$$

$$R_h = \frac{A_c}{p} = \frac{(\theta - \sin\theta\cos\theta)}{2\theta}R \quad (2.23)$$

2.18.3 Froude Number

Open channel flow is also classified as subcritical, critical, or supercritical, depending on the value of dimensionless Froude number defined as,

$$Fr = \frac{V}{\sqrt{gL_c}} \quad (2.23)$$

Where g is the gravitational acceleration, V is the average liquid velocity at a cross section, and L_c is the characteristic length. $L_c$is taken to be the flow depth y for wide rectangular channels. The Froude number is an important parameter that governs the character flow in open channels. The flow is classified as.

Fr< 1 Subcritical or tranquil flow

Fr = 1 Critical Flow (2.24)

Fr> 1 Supercritical or Rapid Flow

This resembles the classification of compressible flow with respect to the Mach number. Indeed the denominator for the Froude number has the dimension of velocity and it represents speed at which a small disturbance travels in still liquid.

Table 2.2: Analogy between the Mach number in compressible flow and the Froude number in open-channel flow

Compressible Flow	**Open-Channel Flow**
$Ma=\frac{V}{c}$	$Fr = \frac{V}{c_o}$
Ma < 1 Subsonic	Fr< 1 Subcritical or tranquil flow
Ma = 1 Sonic	Fr = 1 Critical Flow
Ma > 1 Supersonic	Fr> 1 Supercritical or Rapid Flow

Consider the flow of liquid in an open rectangular channel of cross sectional area $A_c$with a volume flow rate of $\dot{V}$. The critical depth can be expressed as (in general):

$$y_c = \frac{\dot{V}^2}{gA_c^2} \tag{2.25}$$

As in compressible flow, a liquid can accelerate from subcritical to supercritical flow. It can also decelerate from supercritical to subcritical flow.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter describes the methods that will be used in aiding with the research based on the scope that had been given. Other than that, the methodology of the project and the flow chart of the project will be described in this chapter. In deciding the best method to conduct the experiments a review on the limitations and problematic areas in Micro-EDM is described and documented. Thus, the review will clarify the problems that will occur during this project. The processes are illustrated in the flow chart in section 3.2.

3.2 PROCEDURES

Figure below illustrate the flow chart of this project according to the scope given from start (Final Year Project 1) until end (Final Year Project 2). This flow chart will determine the method to accomplish the main objective of this project and will ensure this project is a success. The process flow of the project is represented by the flow chart in Figure 3.1. Initially, the first step is to identify the problem statements, objectives and scope of the project. The problem statement will be based on the literature review on the issues concerning the problematic areas in Micro-EDM. Based on the objectives given the related information will be taken into account and will be analyze to meet the required needs of the main objectives of this project. In the flow chart, to choose the best design of dielectric flushing method is mainly based on previous studies. The second objective is to study on the rectifier circuit and interpret the whole circuit in order to understand the flow of the circuit. The third objective is to analyze the material removal rate and compare the result with the theoretical values that was obtained by previous researchers. Lastly, after the machining process is done an observation is made on the surface finish of the material in comparison with the previous researches to evaluate on the smoothness of the surface finish.

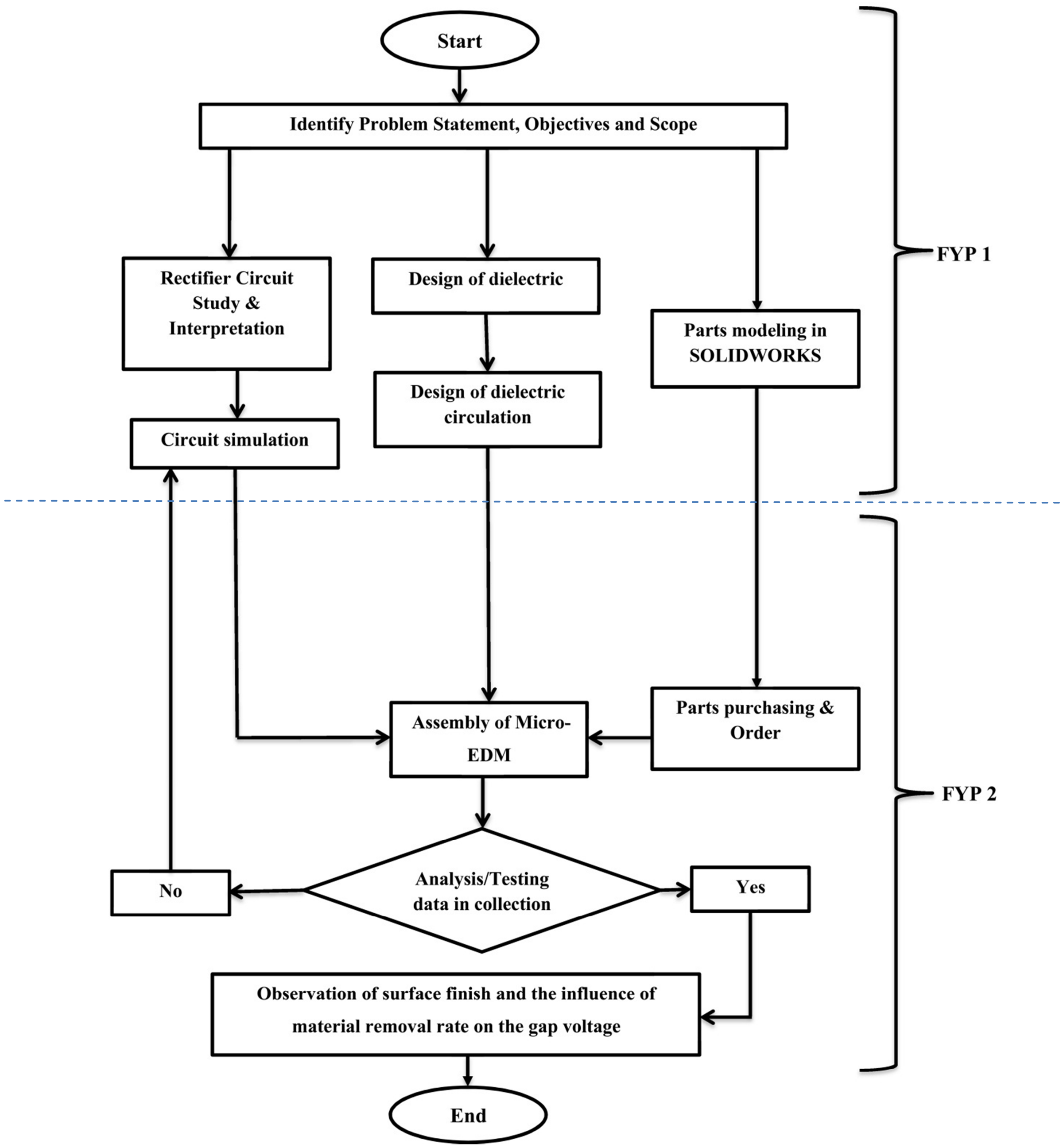


Figure 3.1: Flow Chart for PSM 1 and PSM 2

3.3 CONCEPT OF MICRO-EDM

For this project, the design of the Micro-EDM is basically based on the previous design. The design is shown in Figure 3.2.

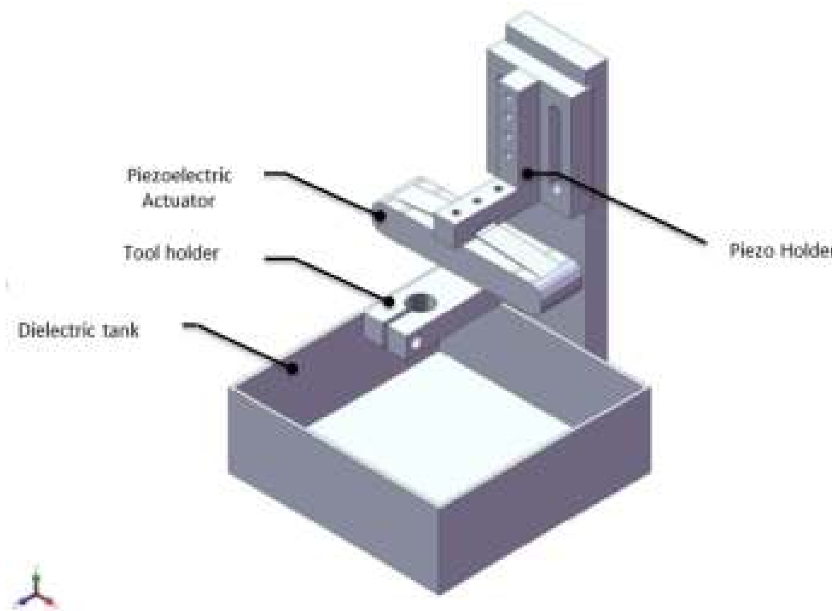


Figure 3.2: Isometric view of the Micro-EDM design, using SolidWork© 2007

In the design the given dimensions are based on the dimensions of the piezoelectric actuator. The piezoelectric actuator is screwed on the tool holder and the piezoholder. The tool holder is attached to the piezoelectric actuator where the piezoelectric actuator will retract and extend as the machining is in process. The piezoelectric properties and the design concept are generally as follows.

3.4 CHOOSING THE AMPLIFIED PIEZOELECTRIC ACTUATORS

Amplified Piezoelectric Actuator (APA) is based on the flexural-extensional principle. An elastic shell bends under the elongation of the piezoelectric actuation. The actuator does not include any weak parts such as flexural hinges, which is an advantage for low cost. The APA is equipped with the strain gauge option where the strain gauge signal will be monitored with a SG75 electronic board. The APA covers an area of performance in terms of force and displacements that is not in the range of direct or bimorph Piezoelectric Actuators. The APAs can detect a slightest short circuit in the system and a control circuit will be developed to ensure the APA will retract when the machining process is short circuited. The APA is an accurate sensor which has a maximum displacement ranging in micro-scale. In this project, the APA is the APA400MML where the properties fulfill the requirement of the designed Micro-EDM. The properties of the APA are based on Appendix A.

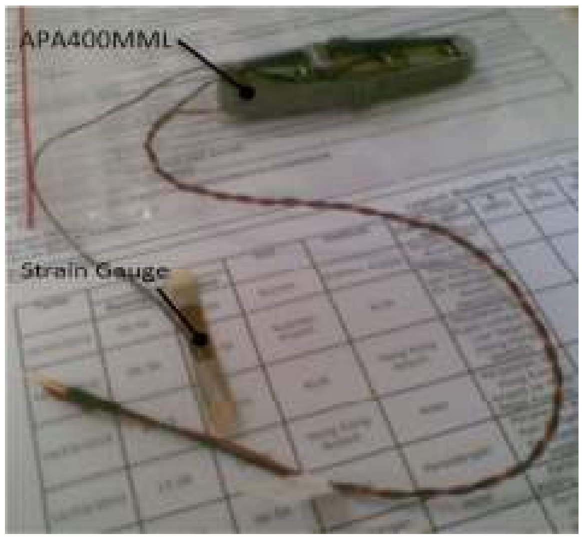


Figure 3.3: APA400MML with strain gauge option

Figure 3.4: Micro-Actuator Control System

3.5 DESIGN OF THE CONTROL CIRCUIT IN MICRO-EDM

The control circuit is designed based on the basic requirements of the Micro-EDM where it consists of three main components. These components are the rectifier, multiplexer and a Pulse Width Modulator (PWM). The purpose of the rectifier is to change the signal received from the sensor of AC to DC signals. The negative voltage signal is only an input that is processes by the rectifier and the positive input is processed by the Operational Amplifier (OpAmp) with the aid of the multiplexer. These signals are controlled by the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET). The MOSFET transistor gate only allows unfamiliar or unidentified signals to be processed by the rectifier. Then the signal will be converted to DC signals, after that the signals will be sent to the summing type OpAmp. At the same time positive signals from the electrode will be compared with the comparative type OpAmp by setting the reference voltage as the limit to prevent the tool from getting near to the workpiece that will cause high tool wear and short circuit. If the signal voltage is higher than the reference voltage, the multiplexer will send a signal to the summing OpAmp to retract the piezoelectric actuator that is in the same time connected to the tool electrode. These signals are observed by the PWD that will convert the signal to the display monitor.

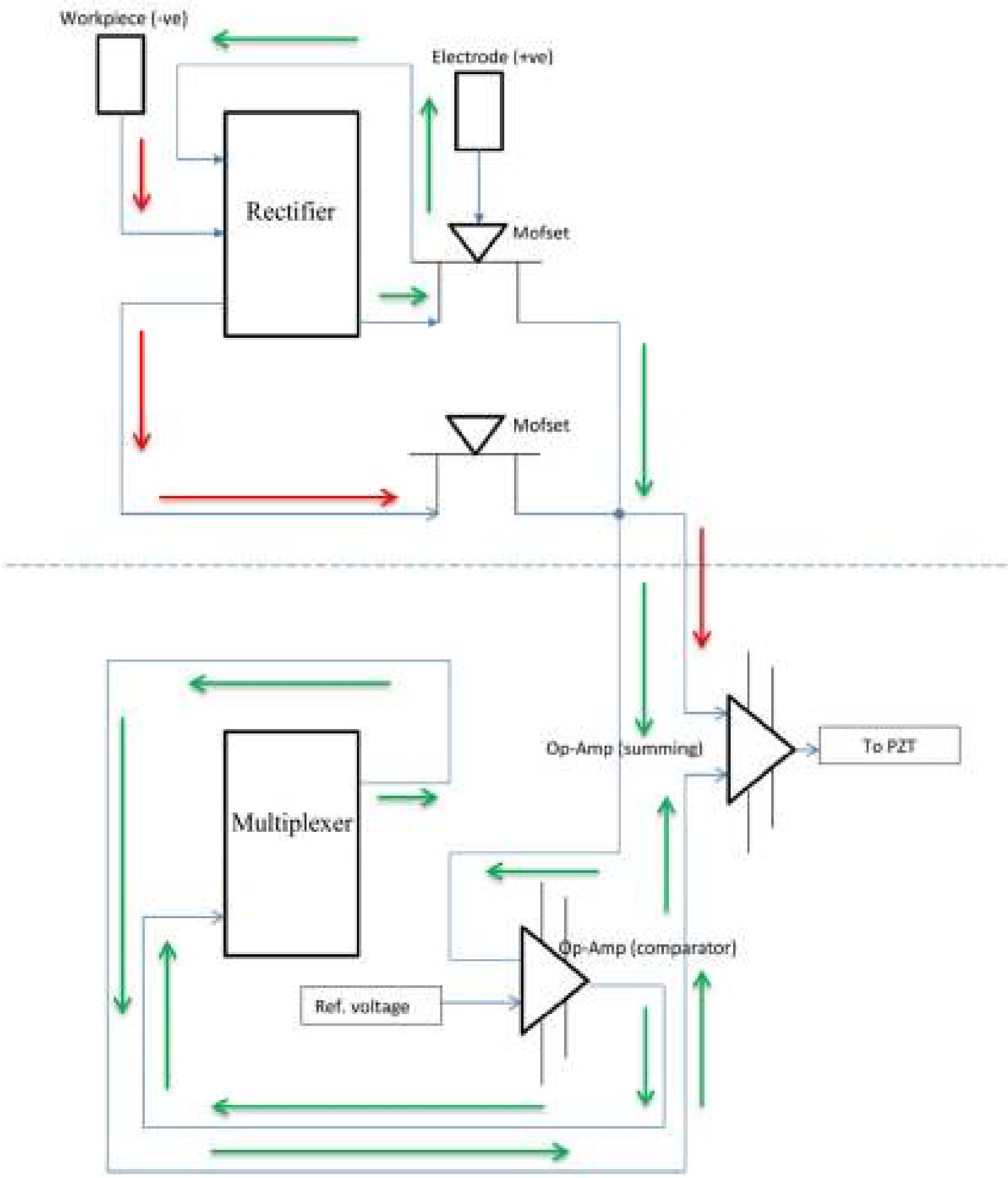


Figure 3.5: Simplification of the Micro-EDM control circuit

3.6 MEASUREMENT OF THE MACHINED DEPTH

The exact length of the Z-axis depth is unable to measure because of lack of equipment in the laboratory. Therefore, an old method to measure the depth was used which is illustrate in the figure below. The initial position of the microscope is to focus on the surface of the workpiece (Z1), and then the reading is taken. After that, the microscope is focused on the machined depth of the workpiece (Z2). After Z1 and Z2 readings are taken then the value of Z is known.

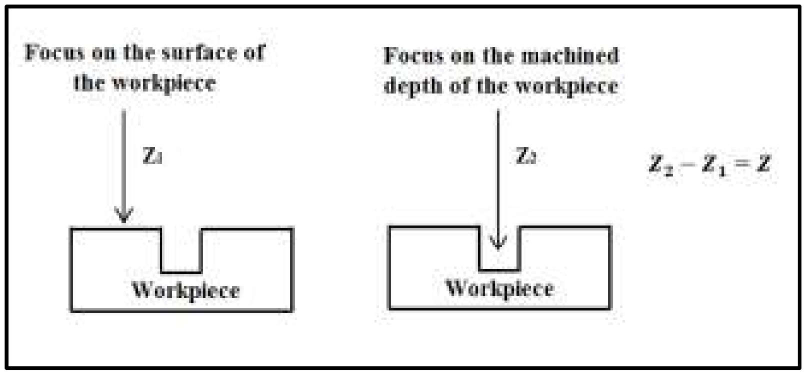


Figure 3.6: Measurement method for machined surface depth

3.7 MATERIAL REMOVAL RATE IN MICRO-EDM

In Micro-EDM the material removal rate is essential in order to ensure a precise and accurate machining. The material removal rate is influenced by the surface roughness and gap voltage. In micro scale machining in Micro-EDM the gap voltage ranges from 30-50V. The analysis flow chart for the material removal rate is shown in Figure 3.7.

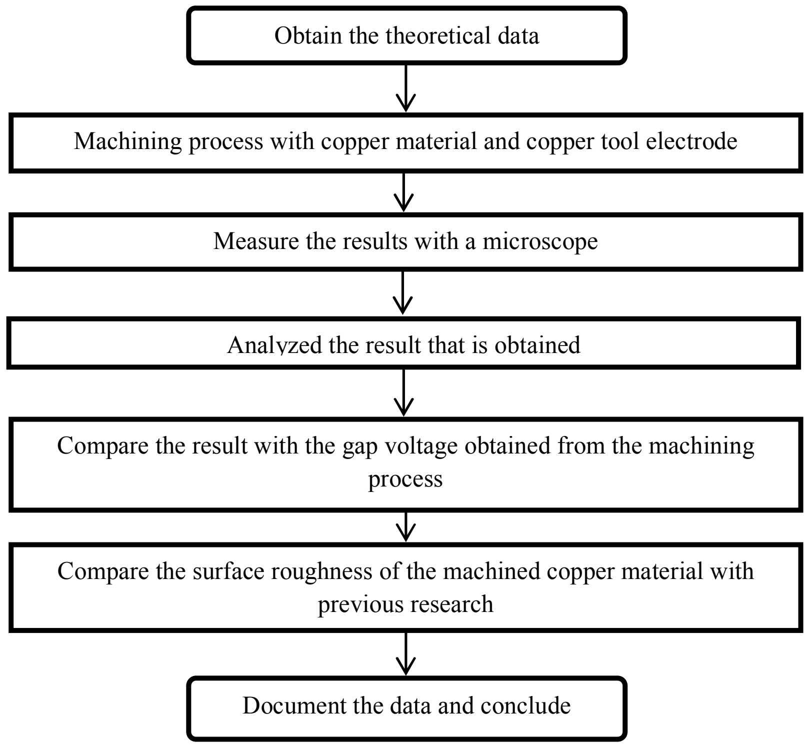


Figure 3.7: Analysis flow chart to measure the material removal rate and surface roughness

3.8 TOOL HOLDER ANALYSIS

The tool holder for the PZT is one of the most important parts in the machine. An evaluation of the part is done to ensure the design can withstand the load that will be subjected to the tool holder when the machined is fully fabricated. The analysis will be done in ALGOR by implementing the load on the tool holder holding mechanism.

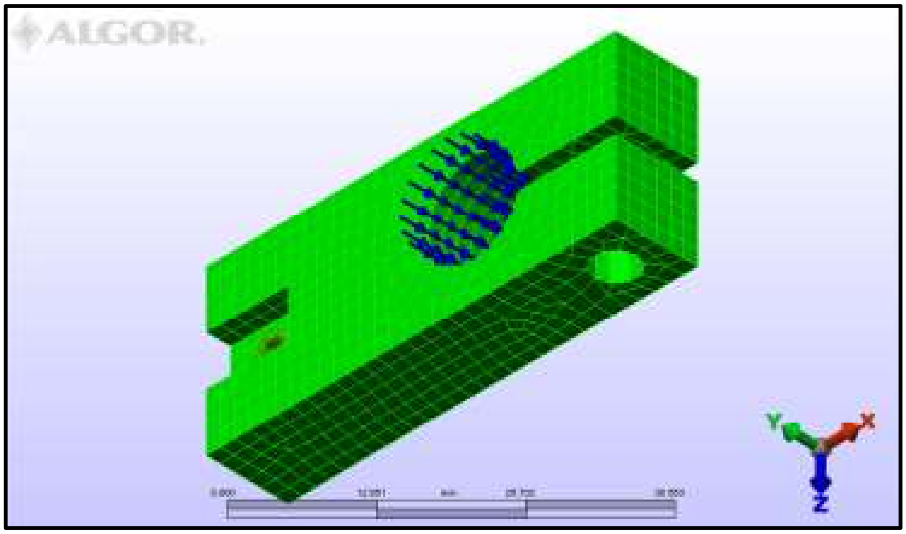


Figure 3.8: Analysis of tool holder using 304 Stainless Steel Annealed

The load is also applied where the PZT will be screwed on. This is because the weight for the PZT is also taken into consideration to obtain a safer design so that the fabricated tool holder design will not fail during machining process.

3.9 PROPOSED DIELECTRIC CIRCULATION SYSTEM

Mainly there are four types of flushing, pressure, suction, external and pulse flushing. The most important factors in EDM are to have proper flushing. Flushing is important because eroded particles must be removed from the gap for efficient cutting. Proper flushing depends on the volume of oil being flushed into the gap rather than the flushing pressure. High flushing pressure can also cause excessive electrode wear by making the bounce around in the cavity. Generally the ideal flushing pressure is between 0.2 to 0.33 bars. Efficient flushing requires a balance between volume and pressure. Roughing operations, where there is a much larger arc gap, require high volume and low pressure for the proper oil flow. The proposed design of the flushing or dielectric circulation system was the using the pressure flushing through the workpiece. The flushing method shown is the pressure flushing where the dielectric fluid is forced through a workpiece mounted over a flushing pot. It is shown in figure 3.9.

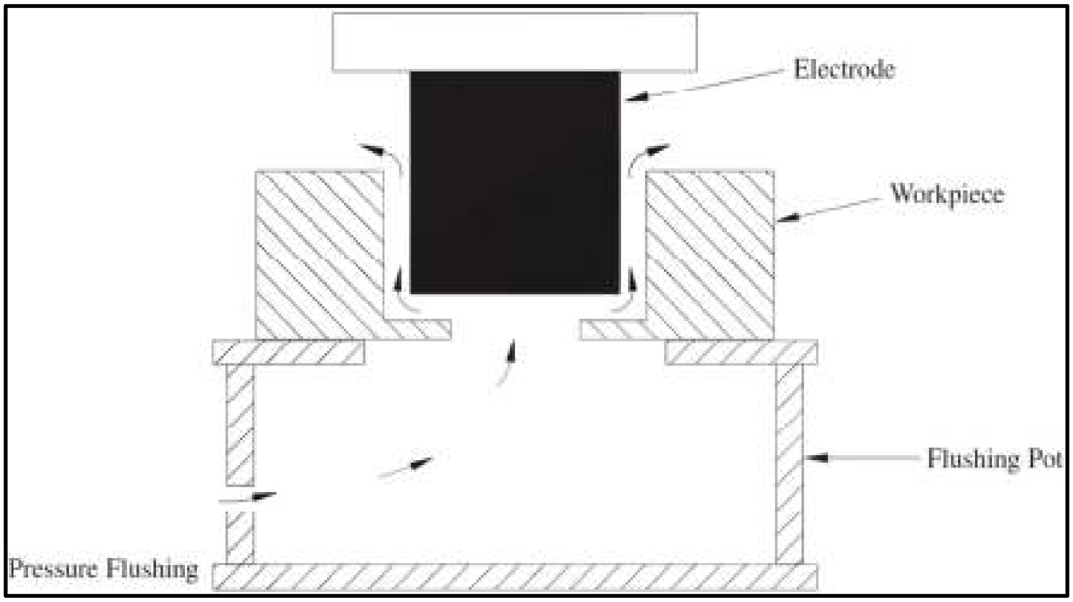


Figure 3.9: Pressure flushing through the workpiece

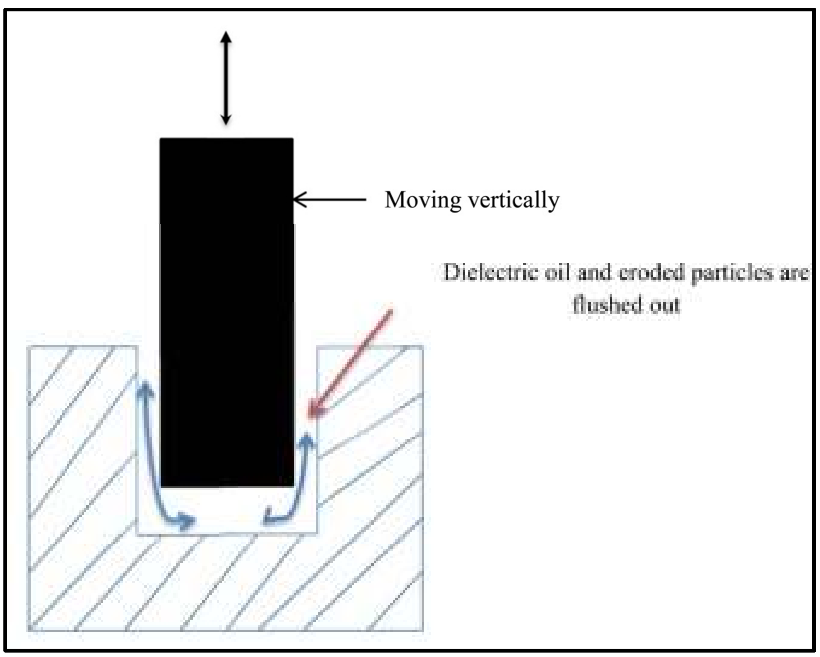


Figure 3.10: Vertical flushing

In figure above, the proposed design is called vertical flushing. In vertical flushing, the electrode moves up and down in the cavity. This up and down motion causes a pumping action which draws in fresh dielectric oil. Many machine are now equipped with jump control which causes the electrode to jump rapidly in and out of the cavity which aids in flushing out the eroded particles as illustrate in figure 3.10.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

From the previous chapter, a design of a control circuit and Micro-EDM is shown. The completed Micro-EDM with a piezoelectric tool feed system is shown in this chapter. The result for the material removal rate and surface roughness is also documented in this chapter where the discussion is based on the comparison with the previous studies conducted by other researchers. The theoretical values are taken from previous research and compared to the results that we have obtained from the machining of the copper workpiece. However, previous studies used other components such as servo motor for their tool feed system where the developed Micro-EDM in this design is based on the piezoelectric tool feed control system. The piezoelectric actuator is controlled by the Linear Amplifier LA75B.

4.2 ANALYSIS OF TOOL HOLDER IN ALGOR SOFTWARE

The tool holder for the Micro-EDM is a crucial part because it holds the PZT in place and holds the tool electrode (copper). This part of the machine is subjected to loads including the weight of the PZT. The use of Stainless Steel Annealed as the material for the tool holder is taken in consideration at first where the result is promising and the material is chosen as the material to fabricate the Micro-EDM tool holder and the reservoir tank. The value of the Ultimate Tensile Strength (UTS) for Stainless Steel Annealed is 568 MPa. Thus, the endurance limits for the tool holder can be known to be 284 MPa since the UTS is lower than 1400 MPa the equation $0.5S_{ut}$ can be implemented. From the figure the maximum stress that was obtained is 279.102 MPa for a given load of 0.3 kg. Thus, the design and material is suitable to use in order to develop the Micro-EDM.

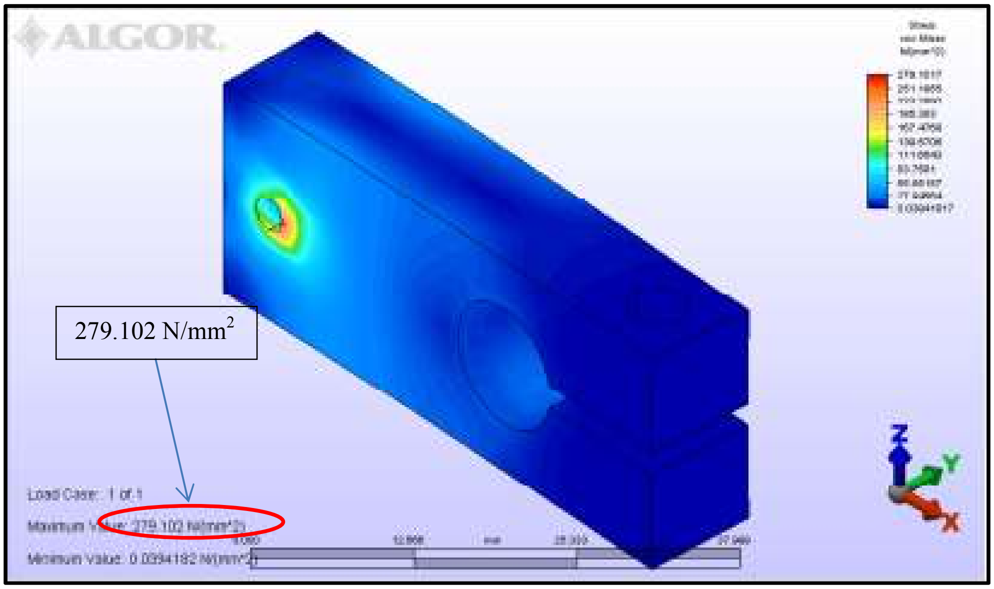


Figure 4.1: Analysis of tool holder in ALGOR using 304 Stainless Steel Annealed

4.3 COMPLETE DESIGN OF THE DEVELOPED MICRO-EDM

The fabrication process for the Micro-EDM is about a few weeks where the manufacturer has been given instructions on how to produce the machine and what are the parameters that are essential to manufacture the Micro-EDM. The design is presented to the manufacturer and the design and concept is accepted. The control circuit is tested with the new tool feed system which is by using the APA400MML. This newly developed designed is to compare the previous design which is based on servo motor as the tool feed control system. In comparison, this design is more accurate because the maximum displacement for the APA400MML is 400 micron. The Linear Amplifier is designed to drive a capacitive load like Piezoelectric Actuator with extremely low noise. This device can perform amplifying operations in the -20/50V range. The Linear Amplifier is equipped with an AC/DC converter LC75B board. An overview of the machine is shown in figure 4.2.

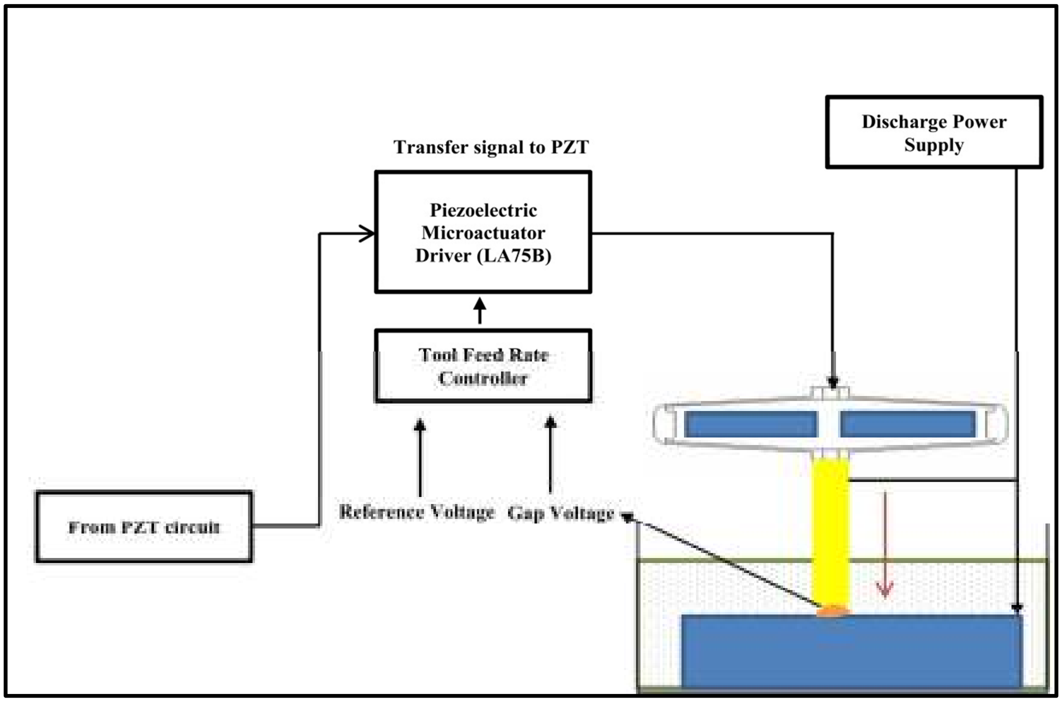


Figure 4.2: Block diagram of the developed Micro-EDM

The sequence of the machine is simple where the piezoelectric actuator acts as a sensor that can retract the tool electrode when short circuit occurs. Since the maximum displacement for the piezoelectric actuator is only 400 microns the machining process must be observed most of the time. This result in, when the Micro-EDM is in the short circuited state the machining process is disrupted where there is no spark generation on the copper material. Previous researcher uses a servo feed control system to control the gap. This will result in frequent short circuit in the machining process. To optimize the machining process the piezoelectric actuator is chosen as the sensor to retract the tool electrode instead of the servo motor. The advantages of the piezoelectric actuator is it has high frequency response and high resolution to meet the electrode drive performances of short circuit back and has high precision feed control. A normal machining gap voltage can be found at 35-50 V. The figure shows a basic principle of the Micro-EDM machining process. The PZT will retract when the gap is small between the electrode and workpiece. With this short circuits can be avoided during the machining process.

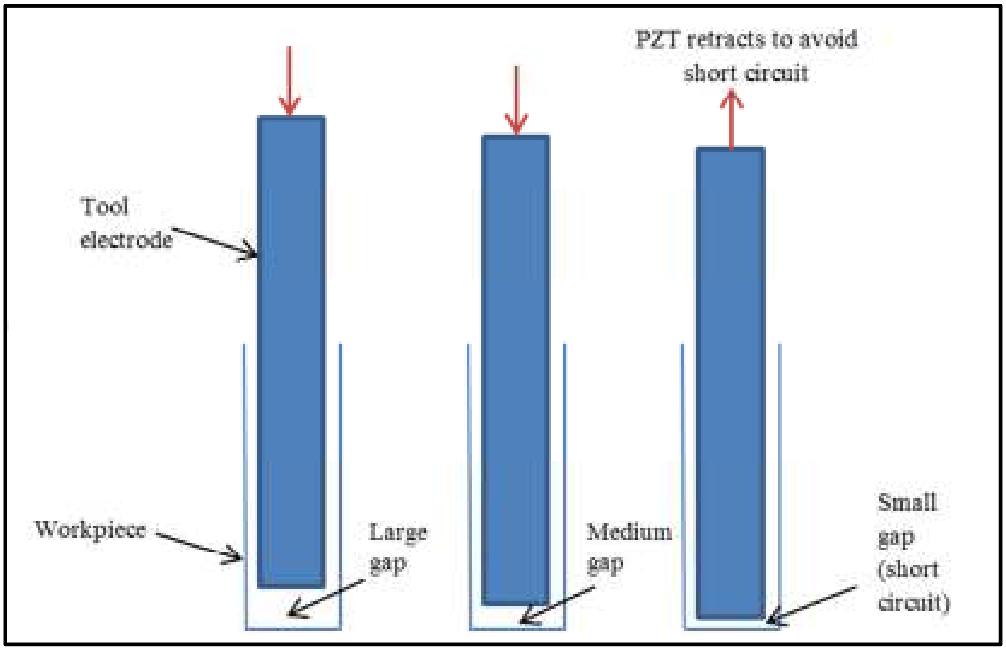


Figure 4.3: Principle of the developed Micro-EDM

4.4 MATERIAL REMOVAL RATE OF THE MACHINING PROCESS

The experiments are conducted with three different area and the parameters is listed in table 4.1. Three experiments have been conducted by using the copper workpiece and the experiment values are stated in table 4.2. The machining time varies in order to monitor the tool condition during machining considering that the Micro-EDM dielectric flushing is not available. Dielectric flushing is an important process for the Micro-EDM machining whereas the flushing will wash away all the unwanted metal particles that is trapped on the machined surface and on the tool electrode. The machine is not equipped with flushing and these results in the carbon decomposition on the tool electrode and workpiece. Carbon decomposition that exists on the tool electrode and the workpiece will result in inaccuracy during the machining process.

Table 4.1: Experiments parameters

Parameters	Units
Supplied Voltage	110 V
Gap Voltage	45- 49 V
Current	1.28A
Workpiece	Copper (thickness = 5mm)
Electrode	Copper: Rectangular shape(10mm(w)x0.1mm(t)x1mm(h))
Tool Feed Control	Piezoelectric Actuator (APA 400MML)

Table 4.2: Data of experiments on Material Removal Rate (MRR)

No. of exp.	Removed Depth from W/piece (micron)	Removed Length from W/piece (mm)	Removed width from W/piece (mm)	Machining Time (Min)	Gap Voltage(V)	MRR (mm^3/min)
1	18	0.984	0.1582	13	36.24	2.1554 $x10^{-4}$
2	15	0.871	0.06397	6	46.13	1.393 $x10^{-4}$
3	28	0.882	0.06470	10	42.82	1.598$x10^{-4}$

The table shows removed depth, removal length from the workpiece and the machining time of the Micro-EDM. From the calculation of the MRR we can induce that as the machining time increase the material removal rate will gradually increases. The depth, removed length of the workpiece and removed width of the workpiece are obtained from the microscope. The measurement of these parameters are not accurate and precise because the lack of high technology that can measure the exact dimensions. The data on table 1 is based on estimation of the dimensions by using a microscope. The data was taken by using an old method to measure a micro-level depth.

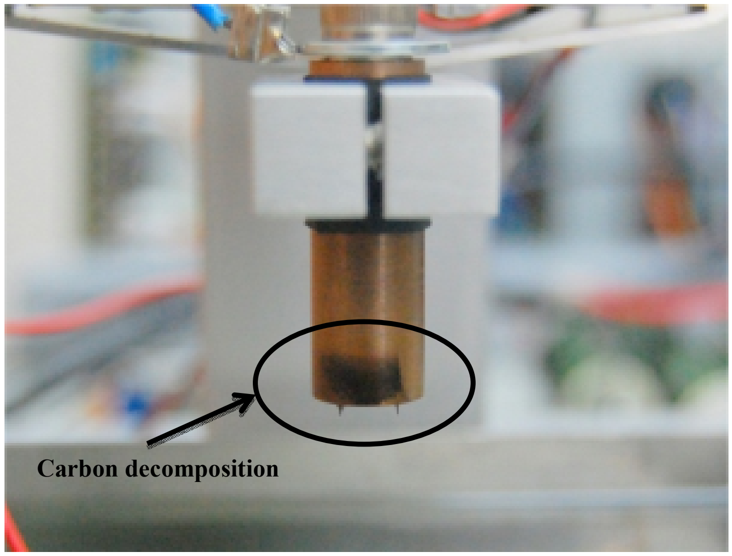


Figure 4.4: Carbon decomposition on the tool electrode after machining

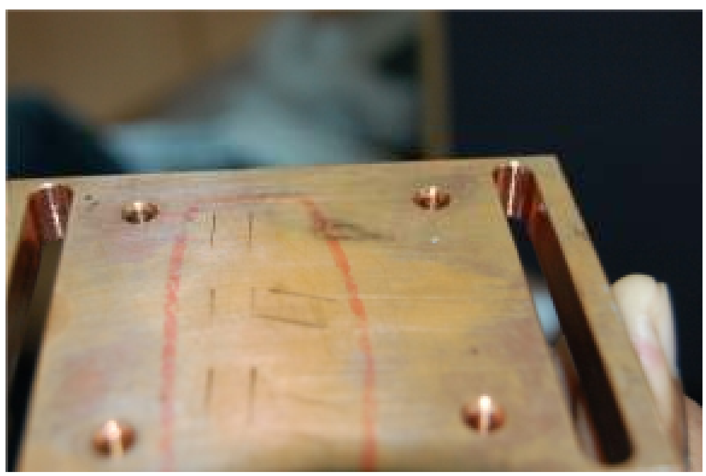


Figure 4.5: The machined surface of the copper workpiece

The scratches on the workpiece show the machined surface of the Micro-EDM. The absence of dielectric flushing has made carbon to decompose on the machined surface.

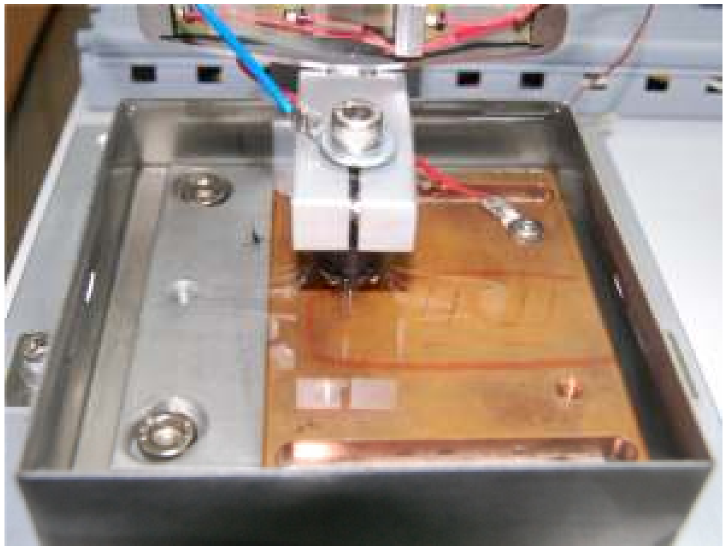


Figure 4.6: Copper workpiece machining processes

Observations are made on the tool electrode and the workpiece and there is a lot of carbon decomposition trapped on the surface of the tool and workpiece as you can see in Fig. 4.4 and Fig. 4.5. This is because there is no dielectric flushing flow in the system and that results in carbon decomposition in the tool and workpiece. The chosen dielectric fluid is kerosene where kerosene has low thermal conductivity and low ignition temperature. Carbon decomposition will disrupt the accuracy of the machining of the workpiece. The spark produces bubbles that indicate the machining process is still commencing.

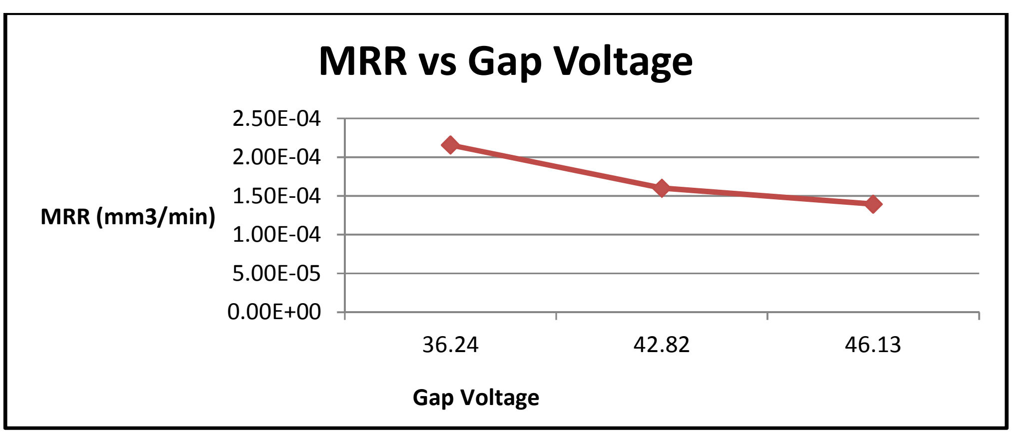


Figure 4.7: Material Removal Rate versus Gap Voltage

The data for the MRR is compared with the gap voltage obtained during the machining process and the MRR decreases as the gap voltage increases. The material removal rate decreases when gap voltage is getting higher. The space between electrode and workpiece becomes larger when a longer bridging time of neutral particles and ions is caused by the increase of gap voltage. The electrical discharge period also becomes longer, reducing the efficiency of the EDM (Wu. et.al., 2009). Current waveform with larger peak current and longer discharge duration will result in higher material removal rate. Longer pulse duration is used in rough machining process. However, longer pulse duration with lower peak current result in lower tool electrode wear and better surface roughness.

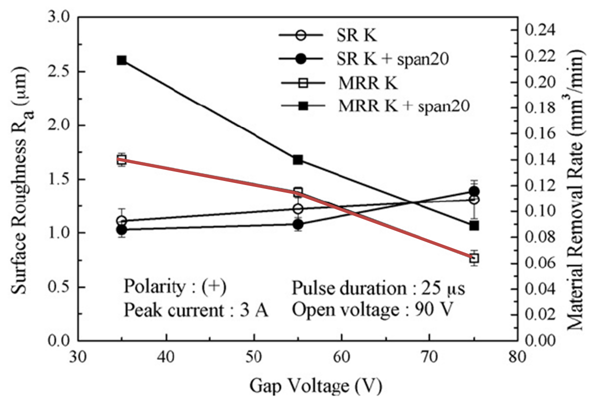


Figure 4.8: Influence of gap voltage on surface roughness and material removal rate: (SR) Surface roughness, (MRR) Material Removal Rate, and (K) kerosene

Source: Wu et. al. (2009)

The figure above shows the influence on surface roughness and material removal rate and the experiment was conducted by K.L. Wu et. al., 2009. The data that was obtained from the experiments is compared to the previous research data. The red line in the figure is the material removal rate with the use of kerosene as the dielectric fluid. From the figure the higher the gap voltage the lower the material removal rate in the machining process. Thus, the data obtained from the experiment that is conducted by using the copper workpiece is similar to the theoretical data obtained by K.L. Wu et. al., 2009 based on figure 4.8.

4.5 SURFACE ROUGHNESS OF THE MACHINED WORKPIECE

The machined surface is shown in figure 4.9. The figure shows that the surface roughness of the machined profile is not smooth. This is due to the absence of dielectric flushing and no movement on the tool electrode during machining. The surface is still in the roughing stage and further studies will be conducted to ensure a good surface finish can be obtained. The hardness test for the machined surface cannot be obtained due to the lack of apparatus to measure micro-level depth.

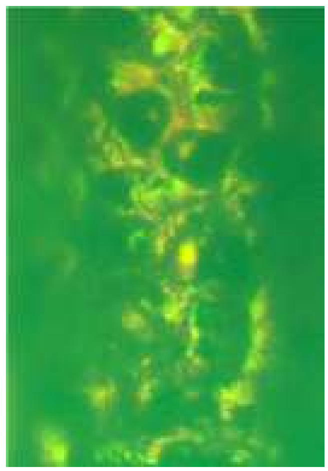


Figure 4.9: Machined groove (Area 1)

This type of surface is only on the first stage of Micro-EDM machining where the surface is only in the stage of roughing process. The second stage of the machining process is surface finishing. The finishing processes are unable to conduct because the developed Micro-EDM capabilities are limited to roughing due to the lack of other important parts that has not been developed. The XY stage controller is absence due to the time constraint of the project and insufficient capital for fabricating the XY stage controller. This prototype can be optimized in further studies and to install the XY stage controller and the dielectric fluid circulation system because with the installation of the XY stage controller a smoother surface finish can be obtained.

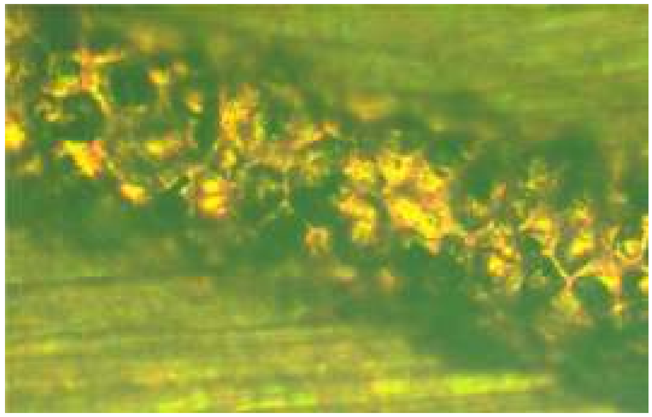


Figure 4.10: Machined groove (Area 3)

4.6 DIELECTRIC CIRCULATION ANALYSIS FOR OPEN-CHANNEL FLOW SYSTEM

The analysis of the dielectric circulation system is based on the open channel flow to calculate the flow velocity and determine the flow is subcritical or supercritical. This study will determine the circulation system that is suitable for the developed Micro-EDM. The analysis was done in CosmosFlow in SolidWorks©. In the software water is used as the medium to simulate the dielectric circulation system. The parameters are as follows.

Table 4.3: Parameters for CosmosFlow Analysis

Parameters	Values/Unit
Inlet Pressure	110272 Pa
Temperature	Constant: 293 K
Outlet Pressure	101328 Pa
Volume Flow Rate	3.667e-5 m^3/s
Mass Flow Rate	4kg/s

The result for the analysis is based on Fig. 4.11. Where the maximum velocity the dielectric fluid can achieve is 3.34484 m/s. The value of the inlet pressure is assumed to be 110.272 kPa where it is also influenced by the pump pressure. The mass flow rate is assumed to be 4kg/s and the outlet pressure is 101.328kPa according to the atmospheric ambient pressure. The value of the velocity was calculated theoretically and the max velocity was 2.05434m/s. The theoretical calculation involves the theory of the Open-Channel Flow of the dielectric circulation. From the theory, the dielectric flow is Supercritical where the Froude number is larger than 1. This results in fast flow in the dielectric circulation system where the flow is efficient for dielectric flushing of unwanted debris that produced during the machining process.

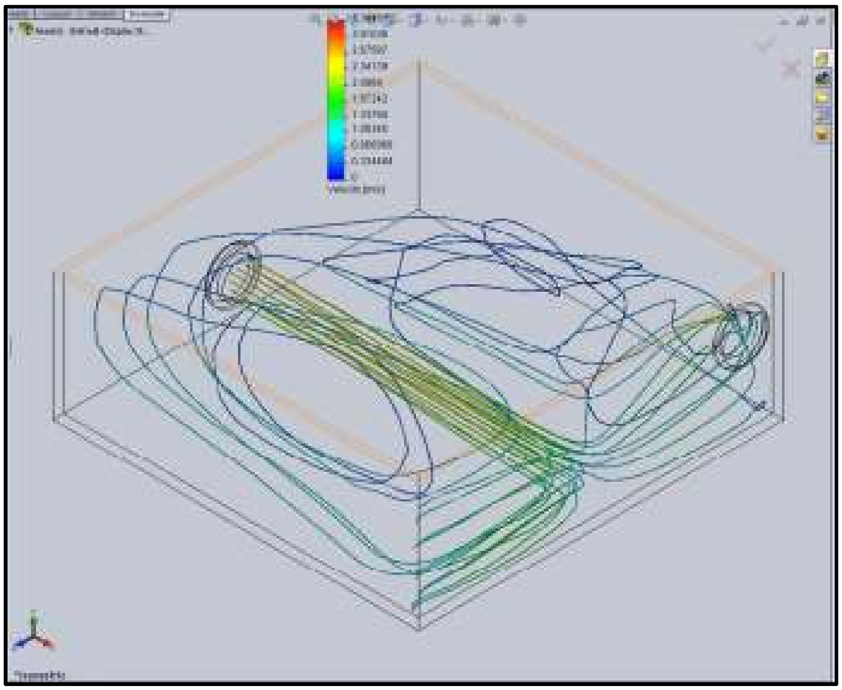


Figure 4.11: CosmosFlow Analysis of dielectric circulation system (Dielectric flow)

4.7 CONCLUSION

The data obtained for the analysis meets the requirement to fabricate the Micro-EDM. The experimental data is better than the previous research where the material removal rate is higher. The material removal rate depends on the gap voltage where the lower the gap voltage the higher the material removal rate. The developed Micro-EDM needs other optimization to increase the material removal rate and high precision cutting of the workpiece. The optimization will be discussed in chapter 5.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 INTRODUCTION

This chapter reveals the conclusion that can be made based on the design and results of material removal rate done in chapter 4.

5.2 CONCLUSION

Material removal rate is an important parameters on EDM and this paper discussed about the influence discharge gap and the process parameters on material removal rate of the material machined. Other than that, EDM flushing is also one of the outmost important parameters where the dielectric flushing will wash off unwanted waste metal particles that will be ionized on the tool electrode that will result inaccuracy in machining compared to the initial condition. Thus, the dielectric flushing and material removal rate is essential in getting an accurate machined profile of the workpiece.

5.3 RECOMMENDATION AND FUTURE PROSPECT

This project can be improved by including XY axis and Z axis motorized system for efficient machining. With the motorized system included the Uniform Wear Method (UWM) can be implemented. The Uniform Wear Method is a method that enhances the material removal rate and increases the precision of machining. However, UWM involves a time consuming empirical approach for selecting the tool paths. Due to financial shortage the dielectric circulation system has not been assembled together with the developed Micro-EDM. Thus, the machining process is disrupted by carbon decomposition resulting in poor material removal rate and tool wear rate. In future Micro-EDM will be the vital machining concept to produce high precision products such as honeycomb filters and fuel injectors for better engine efficiency.

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APPENDIX A

Technical Data Sheet for APA400MML

CEDRAT TECHNOLOGIES

TECHNICAL DATA SHEET | **APA400MML** | **v3.2**

CEDRAT
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➢ TABLE OF STANDARD PROPERTIES OF USE AND MEASUREMENT

The properties defined in the table below, are set up according to the technical conditions of use and measurement. These properties are warranted within their variation range and in compliance with the standard technical conditions of use.

Properties APA400MML	Standard technical conditions	Unit	Nominal values	Min. values	Max. values
Notes		-	Preliminary data	-	-
Max. no load displacement	Quasistatic excitation, blocked-free	µm	384	328	473
Blocked force	Quasistatic excitation, blocked-free	N	189	151	227
Stiffness	Quasistatic excitation, blocked-free	N/µm	0.52	0.42	0.57
Resonance frequency (free-free)	Harmonic excitation, blocked-free, on the admittance curve	Hz	2738	2327	3012
Response time (free-free)		ms	0.18	0.16	0.21
Resonance frequency (blocked-free)	Harmonic excitation, free-free, on the admittance curve	Hz	634	538	697
Response time (blocked-free)		ms	0.79	0.71	0.91
Capacitance	Quasistatic excitation, free-free, on the admittance curve	µF	10.00	8.00	12.00
Max. no load displacement at resonance	Max. harmonic excitation, free-free	µm p-p	297	233	349
Max. voltage at resonance	Max. harmonic excitation, free-free	Vrms	9.00	7.20	10.80
Resolution	Quasistatic excitation	nm	3.84	-	-
Height (in actuation direction)		mm	20.00	19.90	20.10
Length		mm	78.00	77.90	78.10
Width (excl. wedge & wires)		mm	10.00	9.95	10.05
Width (incl. wedge & wires)		mm	11.50	10.50	12.00
Mass		g	47.5	-	-
Standard mechanical interface	2 flat surfaces 5*10 mm² with M3 threaded hole	-	-	-	-
Standard electrical interface	2 PTFE insulated AWG30 wires 150 mm long with Ø 1 banana plug	-	-	-	-

➢ PROPERTIES STANDARD TECHNICAL CONDITIONS OF USE AND MEASUREMENT

Free-free : The actuator is not fixed
Blocked-free : The actuator is fixed to a mechanical support assumed infinitely stiff
Quasistatic excitation : AC voltage between –20 and 150 V at 1 Hz
Harmonic excitation : Voltage of 0.5 Vrms, sinusoidal mode from 0 to 100 kHz
Max. harmonic excitation : Voltage defined by the measurement of max. displacement, sinus at resonance frequency
Displacement measurement : Laser interferometer, capacitive displacement sensor
Admittance measurement : HP 4194 A electrical impedance analyser
Environment : Ambient temperature (15-25°C) and dry air (Humidity < 50 % rH)

Any technical conditions of use, different from those defined above, can lead to temporary or definitive alterations of properties. Thank you to contact CEDRAT TECHNOLOGIES before using actuators under non standard technical conditions.

➢ FACTORY TESTS CARRIED OUT

☒ Test 1 : Electrical admittance vs. Frequency, free-free
☒ Test 2 : Displacement vs. input voltage

➢ EXTRA FACTORY TESTS

☐ Test 3 : Gain and linearity of the sensor
☐ Test 4 : Step response in closed loop
☐ Test 5 : Stability in closed loop

➢ MECHANICAL INTERFACE

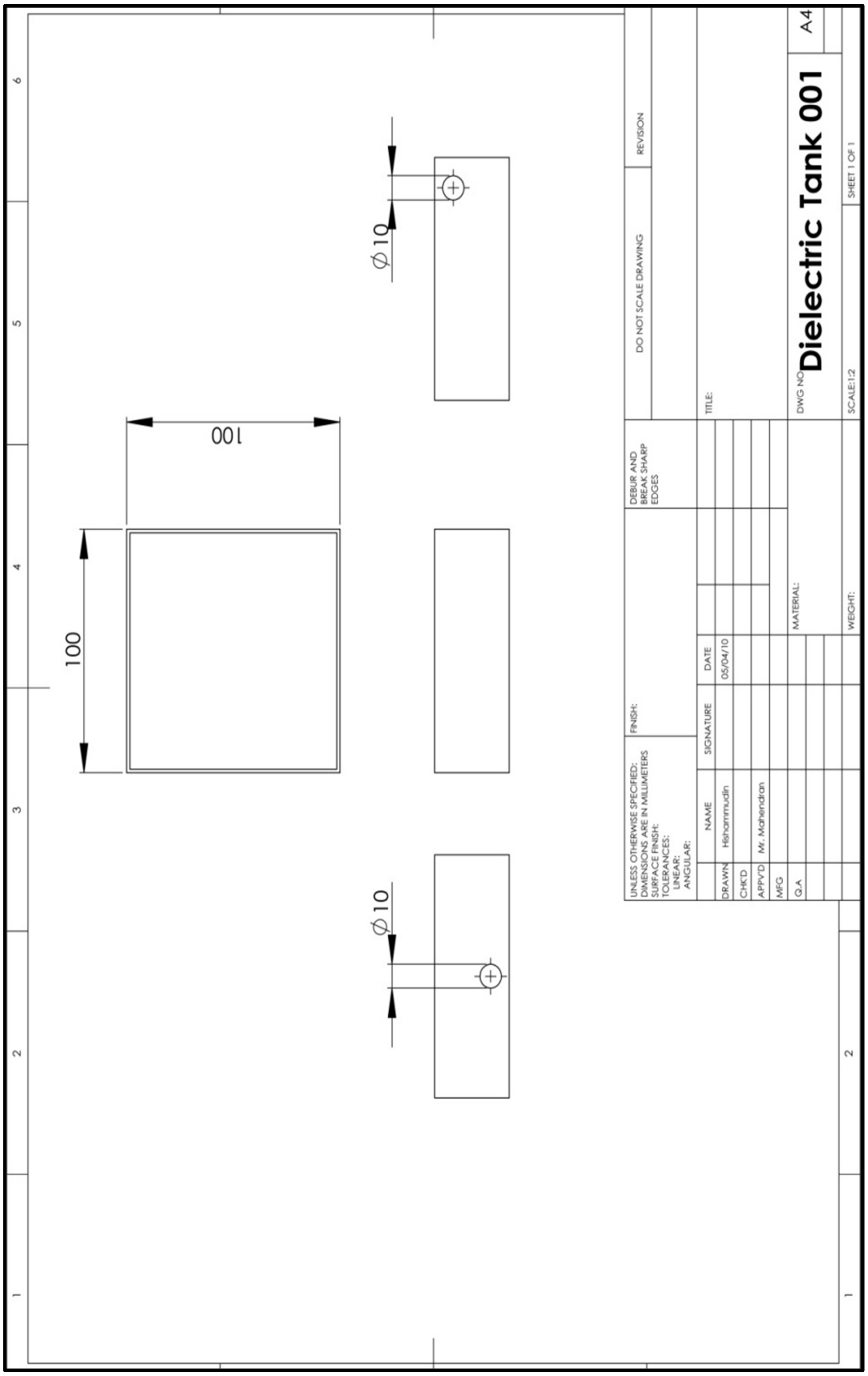
☐ [FI] Flat interface
☐ [H] Flat interface with hole
☒ [TH] Flat interface with threaded hole
☐ [SV] Specific version
☐ [FF] Free-free interface
☐ [SI] Specific interface

➢ AVAILABLE OPTIONS

☒ [SG] Strain gauges
☐ [ECS] Eddy Current proximity sensor
☐ [NM] Non-magnetic
☒ [VAC] Vacuum

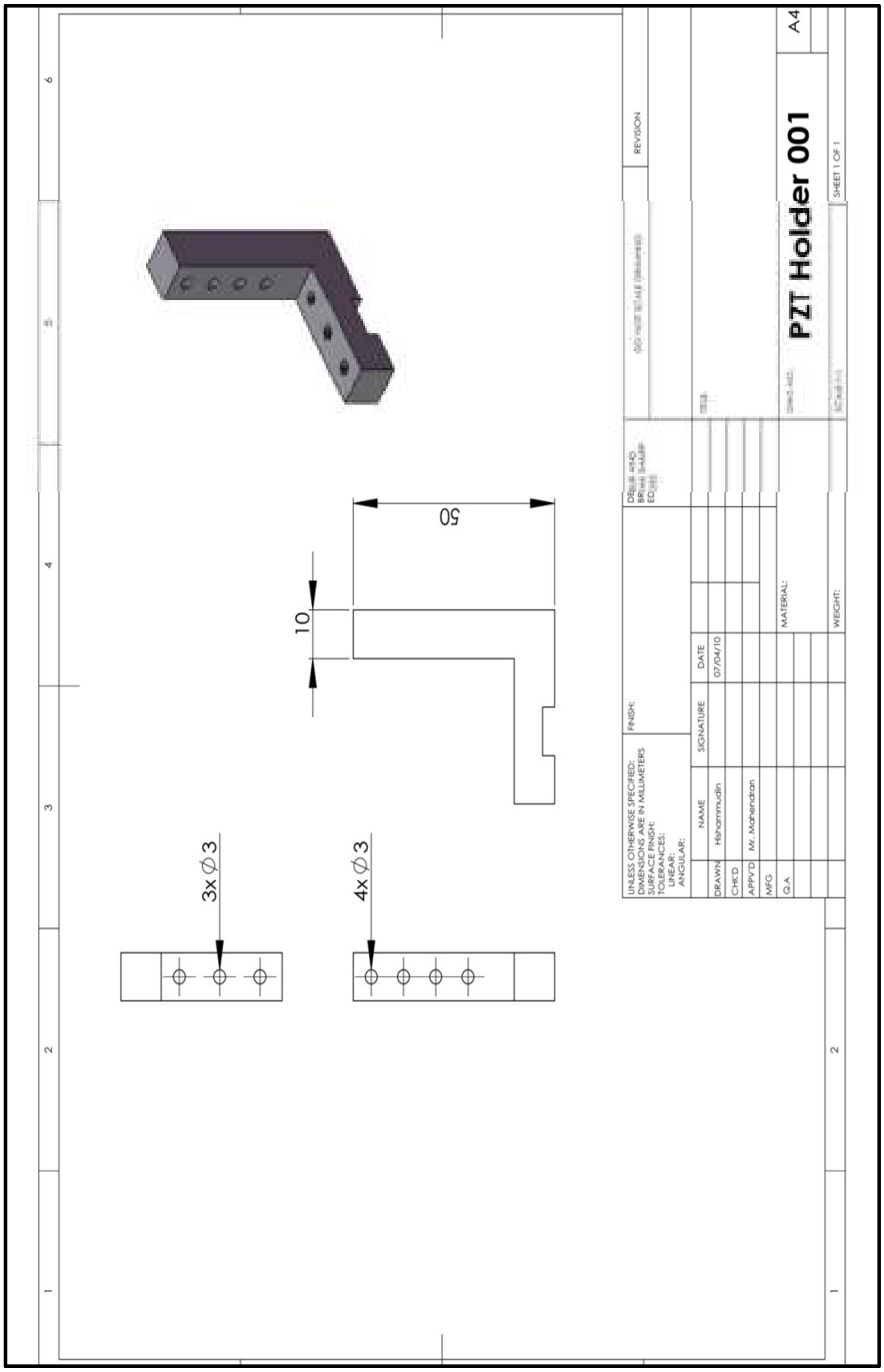
APPENDIX B

2D Drawing of Dielectric Tank



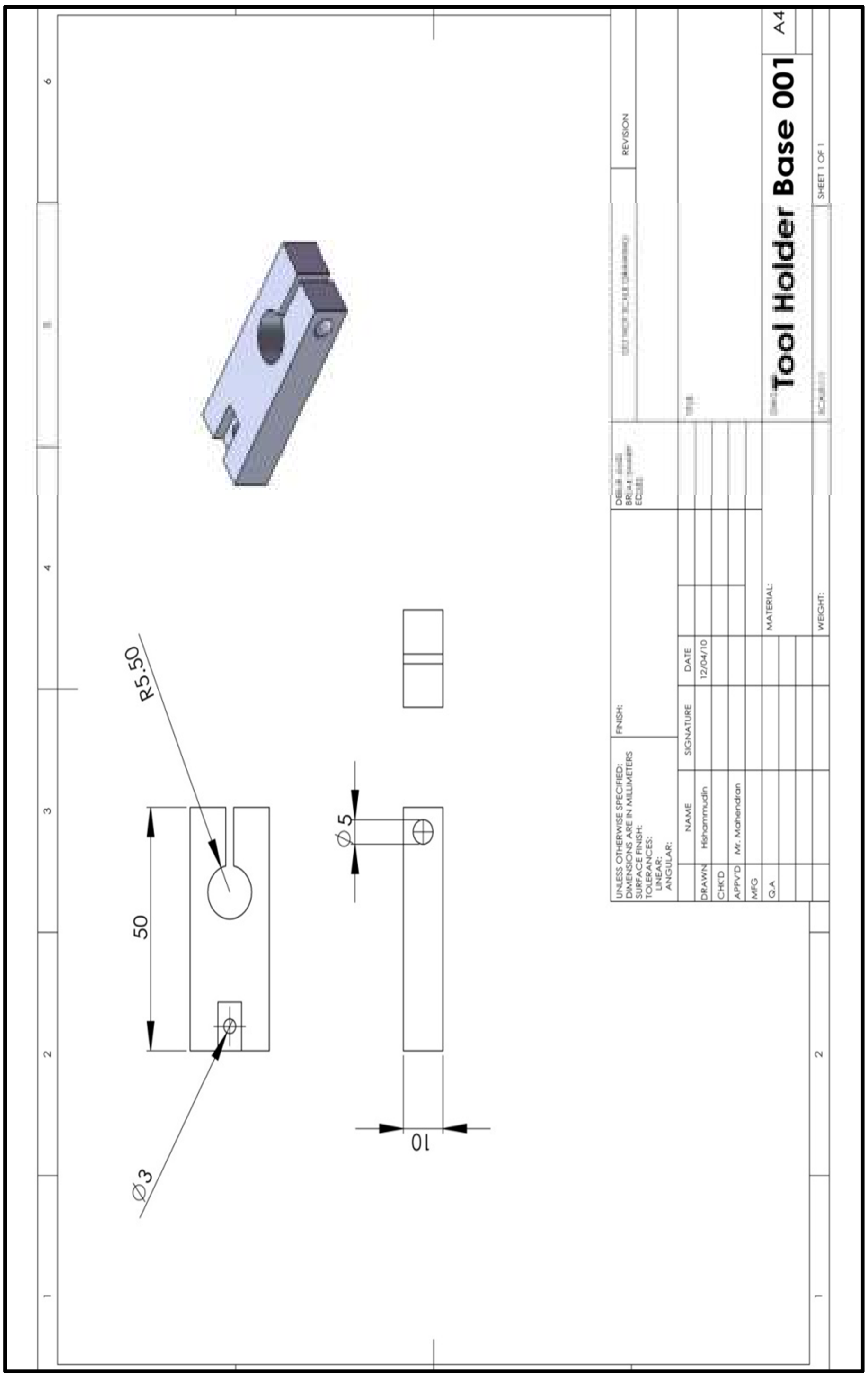
APPENDIX C

2D Drawing of PZT Holder



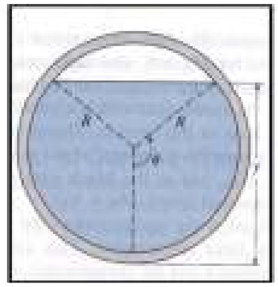
APPENDIX D

2D Drawing of Tool Holder Base



APPENDIX E

Velocity and Critical Depth Calculation in an Open-Channel Flow in Dielectric Tank



Given,

R=2.5mm; $\dot{V} = 3.667 \times 10^{-5} m^3/s$; Assuming $\theta = 135° = 2.356\ rad$

Flow Depth = $3.75 \times 10^{-3} m$

From Equation **2.20**; the flow area,

$$A_c = (2.5 \times 10^{-3} m)^2 (2.356 rad - \sin 2.356 \cos 2.356)$$
$$= 1.785 \times 10^{-5} m^2$$

From Equation **2.21**; the wetted perimeter p,

$$p = 2(2.5 \times 10^{-3} m)(2.356)$$
$$= 0.01178 m$$

$$V = \frac{\dot{V}}{A_c}$$

$$= \frac{3.667 \times \frac{10^{-5} m^3}{s}}{1.785 \times 10^{-5} m^2}$$
$$= 2.05434\ m/s$$

Calculating the critical depth of the flow using **2.25**;

$$y_c = \frac{(3.667 \times \frac{10^{-5} m^3}{s})^2}{\left(\frac{9.81 m}{s^2}\right)\left(1.785 \times 10^{-5} m^2\right)^2}$$
$$= 0.43021\ m$$

Since,

$$y_c > y$$

Thus, the flow is **SUPERCRITICAL**

To check the flow is SUPERCRITICAL

$$Fr = \frac{2.05434}{\sqrt{9.81(3.75 \times 10^{-3})}}$$
$$= 10.71$$