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REAL TIME MONITORING AND COMPENSATION SYSTEM FOR MICRO ELECTRO DISCHARGE MACHINING

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in partial fulfillment of the requirement for the degree of
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2010

Real Time Monitoring and Compensation System for Micro Electro Discharge Machining

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**SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING
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2010

Abstract

The rapid growth in demand for micro parts has urged today's manufacturing industry to establish a reliable technique for micromachining. Micro Electrical Discharge Machining (EDM), the downscaled technique of conventional EDM, provides the capability of machining high strength and electrically conductive materials by means of electrical sparks. The fact that EDM is now the fourth most popular machining process, with sales exceeding all other processes except milling, turning and grinding, shows that it has unique characteristics to become one of the most useful industrial techniques for machining complex three dimensional features.

However, as EDM is a tool-based machining technique, tool wear becomes an unavoidable problem which significantly reduces the machining accuracy. The effect of tool wear becomes more significant in micro EDM than that of conventional EDM. To address this issue, this research work attempts to develop a reliable method to compensate and minimize the effect of tool wear in micro EDM. Real time compensation method is proposed as it provides a better insight into the stochastic nature of the EDM process. The development of the proposed method is conceptualized into several steps in order to build an accurate and reliable compensation system.

The first step of this research work is to develop an analytical model, which is used to estimate the amount of material removal from a single discharge pulse. Existing electro-thermal models were adopted and found to have a reasonable estimation of material removal volume at anode and cathode. The following step is the development of real time monitoring unit for the micro EDM which is used to supervise the ongoing material removal process during machining. The developed unit consists of two main modules; discharge pulse counting module and pulse discriminating module. The characteristics of the pulse distribution were investigated and the findings were used to develop an adaptive speed control module for micro EDM.

Subsequently, the analytical model and the real time monitoring unit were integrated into one setup to estimate the material removal and tool wear volume in real time. This setup is able to perform estimations of material removal volume at various energy inputs, machining depth settings, and material properties. The setup is then incorporated in a real time compensation system. Experimental results show that the proposed system can reduce

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the effect of tool wear and produce more accurate micro holes as compared to other existing methods such as the normal machining method and the uniform wear method. For instance, at 900 μm machining depth setting, the proposed method is able to reduce the dimensional error to 4% only, while the uniform wear method reduces dimensional error to 6%. In addition, experimental investigations reveal that the proposed method is more reliable than uniform wear method.

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List of Abbreviations

ANN	: Artificial Neural Network
ANOVA	: Analysis of Variance
CCTV	: Closed Circuit Television
CNC	: Computer Numerical Control
CVD	: Chemical Vapor Deposition
DAQ	: Data Acquisition
DC	: Direct Current
DD	: Delayed Discharge
DDS	: Data Dependent System
DOE	: Design of Experiment
EDM	: Electrical Discharge Machining
LCC	: Inductor – Capacitor – Capacitor
MEMS	: Micro Electro Mechanical Systems
MRR	: Material Removal Rate
MST	: Micro System Technology
ND	: Normal Discharge
NI	: National Instrument
NLB	: Non Lithography Based
PCD	: Polycrystalline Diamond
PCI	: Personal Computer Interface
PD	: Pulse Discriminating
PDE	: Partial Differential Equation
PHSM	: Point Heat Source Model
RC	: Resistor – Capacitor
RF	: Radio Frequency
SC	: Short Circuit
SR	: Surface Roughness
SWC	: Super fine Tungsten Carbide
TWR	: Tool Wear Ratio
UWM	: Universal Wear Method
WEDG	: Wire Electrical Discharge Grinding
WEDM	: Wire Electrical Discharge Machining

Nomenclature

α	: Thermal diffusivity (m^2/s)
β	: Dimensionless radius for PHSM
C	: Capacitor value (pF)
C_{MR}	: Material removal factor
C_p	: Specific heat (J/kg.K)
C_{TW}	: Tool wear factor
d	: Crater diameter (μm)
$D_{electrode}$	: Diameter of tool electrode (mm)
D_{hole}	: Approximated hole diameter (mm)
$erfc$	: complimentary error function
E	: Complete elliptic integrals of the second kind
E_{in}	: Discharge energy input (μJ)
F_a	: Combination of fraction of energy and fraction of molten area expelled in anode
F_c	: Fraction of energy transferred to cathode
g	: Maximum discharge gap
G_t	: Feed rate gain
h	: Crater depth (μm)
I_a	: average discharge current during pulse-on time (Ampere)
I_p	: Peak discharge current (Ampere)
K	: Complete elliptic integrals of the first kind
K_E	: Electric field intensity
K_β	: Non-uniformity coefficient of electric field
K_t	: Thermal conductivity (W/m.K)
L_0	: Electrode length before machining (mm)
L_i	: Electrode length after machining (mm)
L_w	: Machining depth setting of 1 layer milling process (mm)
N_p	: Number of discharge pulse
ρ	: Material density (kg/m^3)
p	: Machining width (mm)
q	: Heat flux (W/m^2)

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θ	: Dimensionless temperature
θ_{crater}	: Crater's edge temperature
r	: Radial distance from the origin (m)
R	: Heat flux radius (μm)
R_a	: Center line average surface roughness (μm)
R_{anode}	: Heat flux radius at anode (μm)
R_m	: Crater melt radius (μm)
R_{max}	: Maximum surface roughness (μm)
S_w	: Cross sectional area of cavity (mm^3)
S_e	: Cross sectional area of electrode (mm^3)
τ	: Dimensionless pulse-on time
t	: Time (s)
T	: Temperature (K)
T_0	: Ambient temperature (K)
T_m	: Melting temperature (K)
T_{on}	: Pulse on time (ns)
u	: Dimensionless radius
ΔV	: Voltage difference between electrodes (Volt)
$\bar{V}$	: Average gap voltage (Volt)
V_a	: average discharge voltage during pulse-on time (Volt)
V_d	: Discharge voltage (Volt)
V_{max}	: Maximum voltage value (Volt)
V_s	: Servo reference voltage (Volt)
V_{OC}	: Open circuit voltage value (Volt)
$V_{crater\ anode}$	: Crater volume at anode (μm^3)
$\bar{V}_{crater\ anode}$	: Average volume of single crater at anode (m^3)
$V_{crater\ cathode}$	: Crater volume at cathode (μm^3)
$\bar{V}_{crater\ cathode}$	: Average volume of single crater at cathode (m^3)
V_{MR}	: Estimation value of material removal volume at workpiece (m^3)
$V_{MR\ actual}$	: Experimental value of material removal volume at workpiece (m^3)
V_{TW}	: Estimation value of total tool wear volume (m^3)
$V_{TW\ actual}$	: Experimental value of total tool wear volume (m^3)
V_{TWL}	: Volume of longitudinal tool wear (m^3)

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V_{target}	: Approximated targeted material removal volume (m ³)
w	: Dimensionless depth
γ	: Dimensionless temperature for PHSM
z	: Vertical distance from the origin (m)
Z	: Machining depth setting for drilling process (mm)
$\%Arc$	: Percentage of arc pulse (%)
$\%DD$	: Percentage of delayed discharge pulse (%)
$\%ND$	: Percentage of normal discharge pulse (%)
$\%SC$	: Percentage of short circuit pulse (%)
$\%SD$	: Percentage of secondary discharge pulse (%)
Δh	: Additional compensation length (mm)
ΔZ	: Required depth of cut for milling process (mm)

List of Related Publications

1. Yeo, S.H., Aligiri, E., Tan, P. C. and Zarepour, H., *A New Pulse Discriminating System for Micro-EDM*, Materials and Manufacturing Processes, 2009. 24:12, p1297-1305
2. Aligiri, E., Yeo, S.H., Tan, P. C. and Zarepour, H., *Benefits of Using Real-Time Pulse Discriminating System in Micro-EDM Monitoring and Control System*, International Journal of Mechatronics and Manufacturing Systems, 2010. v3, no5/6
3. Yeo, S.H., Aligiri, E., Tan, P. C. and Zarepour, H., *An Adaptive Speed Control System for Micro Electro Discharge Machining*, Proc. The 3rd Manufacturing Engineering Society International Conference (MESIC), Spain, 17-19 June 2009.
4. Aligiri, E., Yeo, S.H., and Tan, P. C., *A New Tool Wear Compensation Method based on Real Time Estimation of Material Removal Volume in Micro EDM*, Journal of Materials Processing Technology. 2010. v210, p2292-2303

CHAPTER 1

INTRODUCTION

1.1 Background

The rapid growth of demand for micro products and micro components in electronics, optics, medicine, biotechnology, automotive, communications and avionics industries has forced today's manufacturing industry to develop innovative methods for product miniaturization. Specific micro-products applications include medical implants, diagnostic devices, micro-scale fuel cells, micro-scale pumps, micro-nozzles for high-temperature jets, micro-molds and micro components in daily life products such as inkjet printers [1]. This high demand shows that the trend in manufacturing industry has shifted from conventional machining to precision machining following Taniguchi's curve [2]. A market study done by a joint SEMI/Yole Développement predicts that the worldwide market in Micro Electro Mechanical systems (MEMS) and Micro System Technology (MST), will exceed US\$ 15.8 billion in the near future [3] as shown in Figure 1-1.

Figure 1-1 Total market for MEMS and micro system products, 2007-2012 [3]

To meet this demand, researchers in academia and industry worldwide have been working to develop a variety of micro machining techniques including lithography based MEMS and non lithography based technique (NLB). NLB technique includes micro-drilling,

micro-milling, micro-turning, micro-cutting, micro-grinding, micro-abrasive blasting, micro-abrasive jet machining, micro ultrasonic machining, micro electrochemical machining, and micro electrical discharge machining. Each technique and its sub-technique have their own advantages and limitations. For example, lithography techniques have limitations on restricted choice of workmaterials, inability to produce complex geometries, huge capital investment and inevitable clean-room environment [4]. The comparison of micromachining processes is presented in Table 1-1 [5].

Table 1-1 Comparison of Micromachining Processes [5]

Micro Machining Processes	Geometric Complexity	Range of Materials	Proto-typing	Mass Product-ion	Surface Quality	Afford-ability
Mechanical processes	+	○	+	○	+	+
EDM, ECM, USM	+	○	+	-	○	+
LBM	○	+	+	-	○	○
LIGA	-	-	-	+	+	-
Near net shape processes	○	○	-	+	○	○

+Good ○ Fair -Poor

EDM is a well developed machining technique which has been established for more than 60 years. The fact that EDM is now the fourth most popular machining process, with the machine being sold more than all other machines except milling, turning and grinding [5], shows that it has become one of industries' favorite techniques for machining complex features. This might be attributed to its unique characteristic associated to the material removal process, which employs electro-thermal energy in the form of electrical sparks. The major advantages of EDM process are listed below [6]:

- Cavities with thin walls and fine features can be produced
- Difficult geometry is possible
- The use of EDM is not affected by the hardness of the work material
- The process is burr-free

As negligible force is exerted for material removal process, there will be low, if any, deflection on tool electrode and workpiece thus the use of smaller and finer electrode becomes viable. This gives the EDM possess a good potential to be adopted in

micromachining, which now is known as micro EDM. The capability of micro EDM for fabricating complex 3D microparts has been demonstrated in [7].

As EDM is a tool-based machining technique, tool wear becomes an unavoidable problem which significantly affects machining accuracy. The effect of tool wear becomes more significant in micro EDM since the tool wear in micro EDM is more severe than in conventional EDM. It is reported that the length of the consumed electrode can achieve 92% of the machining depth in micro EDM drilling [8]. This effect can directly influence the accuracy of the machined feature. Tool wear is a critical issue in micro EDM since the requirement for accuracy is more demanding in the realm of micromachining. Reducing the tool wear effect can elevate the overall performance of the micro EDM process.

Minimizing the effect of tool wear can be achieved by employing a high wear resistance tool material or compensating the tool wear. High wear resistance tool materials, such as polycrystalline diamond (PCD) and boron-doped CVD diamond (B-CVD) [9], are normally difficult to machine and may tremendously increase the tool production cost. It is reported that the cost of a part manufactured by EDM method is determined mainly by the tool cost which contributes more than 70% of the total operation cost [10]. Therefore utilizing an expensive tool material may not be efficient to be applied in industries. On the other hand, compensation method can be easily implemented into machining system without giving significant rise in production cost.

Although several attempts have been conducted to compensate the tool wear effect, the outcomes in terms of applicability, practicability, and geometrical accuracy is still far from satisfactory. A new approach is needed in order to address the tool wear issue so that the real capability of micro EDM technique in producing micro scale products can be fully exploited.

In this research work, a new approach in compensating the tool wear is proposed. A system which combines a theoretical electro-thermal model and real time monitoring process is developed in order to estimate the material removal and tool wear volume of a micro EDM process in real time. The electro-thermal model is used to estimate the amount of unit removal from a single spark while the real time monitoring process is used to count the number of discharge pulse and to discriminate micro EDM pulse. The system is then used to design a new compensation method for micro EDM drilling processes. In addition to the

effort for improving the dimensional accuracy, this work is aimed to give a better insight into micro EDM, and a link of the knowledge between the single spark material removal mechanisms and material removal mechanism in machining process.

1.2 Motivation

Several work have been undertaken to address the issue of tool wear in conventional EDM. Ironically, work to deal with this issue in micro EDM is still lacking, although the demand for higher accuracy is magnified at the micro scale.

The stochastic mechanism of material removal in EDM process involves a large number of machining parameters that influence the machining performance. Therefore it is very difficult to perform an accurate offline prediction of tool wear over a wide range of machining settings. A real time monitoring approach is considered as an appropriate method to predict the machining performance for a stochastic process. It can provide better understanding and representation of the actual machining process and offers a remarkable advantage for improving the quality of process performance monitoring. A reliable real time monitoring system can serve as a basic platform of micro EDM system.

The information gathered from the real time monitoring system can be combined with the theoretical single discharge model to perform a real time prediction of material removal and tool wear volume. Since the approach is based on theoretical analyses, it is expected to be applicable for a wide range of machining settings and material properties. The prediction can further be used to develop a reliable real time compensation system. Furthermore, the real time monitoring information can also be implemented in a servo feed control system to improve the machining time of the EDM process. Thus the overall machining performance can be improved.

1.3 Objective

The research work is carried out with the following aims:

1. To develop an appropriate analytical model for micro EDM process
2. To develop a discharge pulse counting module for micro EDM
3. To develop a real time pulse discriminating (PD) module for micro EDM
4. To study the characteristic of pulse distribution during micro EDM machining process.

5. To perform real time estimation of material removal and tool wear volume by combining the developed real time monitoring unit with the micro EDM analytical model.
6. To establish a new real time compensation method for micro EDM

1.4 Scope of work

This research work studies the feasibility of improving micro EDM machining performance using real time monitoring and compensation system. This is done by continuously retrieving the voltage and current waveforms in a discharge gap using the developed data acquisition system.

The first stage of this research work is a thorough literature study to understand the material removal mechanism of single spark process and multiple spark process in micro EDM. The second stage is the development of micro EDM analytical model. The models are adopted and modified from the existing models and they are used to estimate the amount of unit removal from a single spark process. The models are then validated through single discharge experiments.

The next stage of the work is the development of micro EDM real time monitoring unit. A thorough study is conducted to understand the different types of pulse occur in the micro EDM process and their relations with the machining performance. The knowledge gathered is used to establish a new Pulse Discriminating (PD) module for micro EDM. The merit of the PD module is elucidated when it is implemented in the servo feed control module. Experiments are conducted to study the distribution of each pulse type for various machining settings for a better understanding of micro EDM machining processes. Furthermore, a discharge pulse counting module is developed in order to complete the real time monitoring system.

The final stage of this work is to perform real time estimation of material removal and tool wear volume by combining the information gathered from the previous stages. The estimation result is then used to construct a new compensation method where performance validation of the developed system is carried out by means of comparison with normal machining method and uniform wear method.

This work involves the assemble of a complete data acquisition (DAQ) system on an open architecture desktop micro EDM machine. The open architecture of micro EDM is based on a resistor-capacitor (RC) type pulse generator, and three axes actuators controlled by Newport ESP 300 motion controller board. The DAQ devices being used are: digitizer (National Instrument Personal Interface Computer (NI-PCI) 5112), and multifunction DAQ card (NI-PCI 6013). Commercial visual programming language software, LabVIEW™ is used to calculate the crater size for each detected discharge waveform and to perform real time monitoring and control system. The characterization of the experiment results is done by using measuring equipment namely, PLμ confocal imaging profiler, Scanning Electron Microscope (JEOL JSM-5600) and an optical microscope (ROI OMIS II).

1.5 Outline of the report

The following list describes the outline of this report :

- Chapter 1 : Introduction

This chapter covers the background and the underlying idea of the research work conducted. It consists of background, motivation, objective, scope of work and the outline of the report.

- Chapter 2 : Literature review

A critical literature review is covered in this chapter. It covers the basic principle of EDM process and the technology advancement in EDM and micro EDM with special focus on PD system, tool wear, and tool wear compensation system.

- Chapter 3 : Approach to real time compensation system for micro EDM

The proposed steps to develop a real time compensation system for micro EDM are presented in this chapter.

- Chapter 4 : Analytical model of micro EDM process

This chapter covers the development and implementation of micro EDM electro-thermal models for both anode and cathode. The validation of each model using experimental results is also described.

- Chapter 5 : Real time monitoring of micro EDM process

This chapter describes the development of real time monitoring unit for micro EDM process which includes the development of pulse discriminating module and discharge pulse counting module. An investigation on the effect of pulse distribution to the machining performance is described in the subsequent section followed by the application of the PD module to develop an adaptive speed servo control module for micro EDM.

- Chapter 6 : Real time compensation system for micro EDM

The development of a real time erosion volume estimation system is presented at the beginning of this chapter. The development of a new compensation method is then described in the following section where the experimental validations are also provided to demonstrate that developed method is superior to other existing methods.

- Chapter 7 : Conclusions and recommendations for future work

The final chapter presents the concluding summary of the research work and the recommendation for future research work.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews the basic concept of EDM and the state-of-the-art of the cited works in the technological advancement in EDM. The literature review begins with a brief history, followed by the basics of the EDM process which elaborates the sparking principle, EDM configurations, EDM parameters and applications in micromachining. The review focuses on the anode-cathode erosion model, the pulse discrimination in EDM, the tool wear phenomenon, and the tool wear compensation techniques. The last part of the review describes the outcome of the literature review and the correlation with the proposed research work. The framework of the literature review is shown in Figure 2-1.

Figure 2-1. Document map of the literature review

2.1 Brief History of EDM Process

The long history of EDM can be traced back to 1770 when English chemist Joseph Priestly discovered the erosive effect of electrical discharges or sparks [11]. In 1930s attempts were made for the first time to machine metals and diamonds with electrical discharge. V.E. Matulaitis and H.V. Harding developed ‘disintegrators’ to remove broken taps from valuable workpiece material by erosion caused by intermittent arc discharges occurring in air between the tool electrode and workpiece connected to a DC power supply [12].

In 1941, during World War II, the development of spark machining process branched to Union of Soviet Socialist Republic (USSR) and United State of America (USA). In USSR, Dr. Boris Lazarenko and Dr. Natalya Lazarenko were assigned by the government to investigate whether the life of the components could be extended by suppressing sparking between breaker points. Although their experiment was unsuccessful, they found that more uniform and predictable sparking and pitting were created when the breaker points were immersed in oil. This phenomenon was further investigated to seek the possibility of controlled-metal removal through sparks. In 1943, the two Lazarenkos developed a spark-machining process which used a lot of components from automobile ignition system in the electrical circuit. This process then became one of the standard EDM system in use throughout the world [13]. In USA, a valve company assigned Harold Stark, Victor Harding, and Jack Beaver to find a way to remove the broken taps and drills from hydraulic valves [13]. Their idea was to use an electric-etching tool to produce the sparks. After they left the valve company, they patented the automated version of the process. Their work then became the basis for the vacuum-tube EDM machine and an electronic-circuit servo system that automatically provided the proper electrode-to-workpiece spacing for sparking, without the electrode contacting the workpiece [13]. The advent of computer numerical control (CNC) in EDM in the 1980s brought tremendous advances in improving the efficiency of the machining operation, which implied an automatic and unattended machining from inserting the electrodes in tool changer to finished polished cavities [14].

In the late of 1960s, Wire EDM (WEDM) was first introduced to the manufacturing industry. The initiation of CNC into WEDM was done in late of 1970s and it brought about a major evolution of the machining process [15]. In 1990, Takahisa Masuzawa and Takeshi Masaki successfully brought EDM into the realm of micromachining [16, 17]. The

downscaled version of EDM, known as micro EDM, is further developed into: micro-wire EDM, die-sinking micro EDM, micro EDM drilling, and micro EDM milling. Due to the high precision and good surface quality, micro EDM has become a potentially important process for fabricating micro feature and has attracted researchers in academia and in industry to explore its full potential.

2.2 Basics of EDM process

A brief history of EDM describes the pioneering work of the process is to create and control sparks between tool electrode and workpiece in the presence of dielectric liquid in order to remove metallic material. Therefore fundamental insight of how the spark occurs and able to remove material is essential for a better understanding of EDM process.

2.2.1 Sparking Principle

Minute sparks inside the electrode-workpiece gap can be divided into three general phases [18]: preparation phase for ignition (Pre-ignition phase), phase of discharge (Discharge phase), and interval phase between discharge (Post-discharge phase)

2.2.1.1 Pre-ignition phase

The sequence of pre-ignition phase is shown in Figure 2-2. When pulse generator is switched on, voltage will be applied between anode (in this figure is represented as tool electrode) and cathode (in this figure is represented as work-material). The voltage stays constant at open circuit voltage value while current shows a constant zero value. As the tool electrode is traversed down, the inter-electrode gap is getting closer and electric field is created between them. The electric field reaches the highest strength at the place where maximum asperity occurs. Dielectric within this field will be polarized and particles will be concentrated to form a bridge which will define the plasma channel (shown in sequence b). Particles in this term may be in the form of gas spheres, debris from previous discharges and impurities. The polarized dielectric and particles bridge decreases the dielectric resistance and when the applied energy is high enough, they will initiate dielectric breakdown (shown in sequence c). At this point voltage will start to decrease and a slight amount of current is detected. The start of dielectric breakdown indicates the beginning of discharge phase.

Figure 2-2 Sequence of Pre-ignition phase during sparking, adapted from [19]

2.2.1.2 Discharge Phase

Figure 2-3 shows the sequence of the discharge phase inside the electrode-workpiece gap. The electromagnetic field inside the gap triggers the cathode to emit electrons (presented as small ball in the figure) and anode to emit positive ions (presented as big ball in the figure). Since the mass of electron is much smaller than the positive ion, electron travels faster and 95% of the current will be carried out by the electron [20]. This stage is presented in Figure 2-3 (a) where voltage decreases and current increases. The electrons and positive ions will collide with neutral particles, and caused them to split and form positively charged particles and negatively charged particles. This process happens at an explosive rate and known as impact ionization. Ionization point is then defined as the time when the dielectric fluid changes from insulator into electrical conductor [13].

As the protons migrate to the cathode and electrons migrate to anode, electric current flows and this leads to the heating of the dielectric liquid. Dielectric liquid will then be altered

into a shielded gas form, which known as a plasma channel. The electric current flows through this channel and it reaches the maximum (see Figure 2-3 (b)). Temperature as well as pressure will also increase further. It is reported that the temperature in EDM plasma channel is in the range of 4000 K to 12000 K [21-24] while pressure is in the range of few bars [23, 25] to 200 bars [26]. The very high temperature produced by the avalanche collisions generates a localized melting and vaporization at both electrodes. The cathode usually suffers more erosion than that of the anode. At the same time a sphere of gas is created around the plasma channel.

Figure 2-3 Sequence of discharge phase during sparking, adapted from [19]

In sequence (c) of Figure 2-3, plasma channel continues to expand rapidly away from the heat source and cause more melting and vaporization at tool electrode and workpiece. The full expansion of plasma channel diameter is not directly proportional with the resulting crater diameter. A spectroscopic measurement found that the plasma channel diameter can achieved 0.5 mm, five time larger than the crater diameter [27]. During the plasma channel expansion, temperature and pressure increase considerably and withhold the vaporized and molten material in place. The gap voltage and current show a constant value during this

period. Discharge phase is terminated when the input pulse is switched off, indicating the beginning of the next phase.

2.2.1.3 Post-Discharge Phase

When the electricity is cut off, voltage and current will drastically drop to zero. The sudden absence of heat source causes the plasma channel to implode and create a void or vacuum area that draws in fresh dielectric liquid to flush and cool the area. A part of the molten material will be expelled from the surface and trapped in dielectric known as debris. A sudden fall in temperature creates a rapid cooling process and causes some parts of the molten material to re-solidify at the edge and surface of the crater, creating an outer rim shape. The “off” period allows de-ionization process of the dielectric liquid to regain its insulating strength and provides favorable condition for the next spark. It is essential to keep the ‘off-state’ long enough until the dielectric liquid has fully recovered to avoid the occurrences of arcing, which damage the surface of both material and tool electrode. Figure 2-4 shows the sequence of this post-discharge phase.

Figure 2-4 Sequence of Post-Discharge Phase during sparking, adapted from [19]

2.2.2 EDM Configuration

EDM is a machining process which utilizes precisely controlled sparks for material removal. An EDM machine should have a basic configuration as shown in Figure 2-5. The basic components of micro EDM machine are described below.

Figure 2-5 Basic configuration of an EDM machine [28]

2.2.2.1 Pulse Generator

Pulse generator is needed to generate 'on' and 'off' state in a cycle repeatedly. Early EDM machine used relaxation type pulse generator and since then the development of EDM pulse generator has achieved significant advancement. It is reported that the evolution of EDM pulse generator has produced 6 types of pulse generator [29] from simple resistor capacitor (RC) type mechanism until the latest type uses LCC resonant converter [30, 31]. However there are only two types of pulse generators which are widely used in industrial application: RC type pulse generator (Figure 2-6 (a)) and Transistor type pulse generator (Figure 2-6 (b)).

In RC circuit, the resistor holds back the amount of electricity flowing from Direct Current (DC) power supply to the capacitor. The electricity is stored in capacitor until the capacitor is fully charged to its maximum capacity. This charging time produces the 'off' state of the input pulse. When the capacitor is fully charged, it creates discharges from the electrode to the work piece through the gap in form of a spark. This discharging time produces the 'on' state. Transistor type pulse generator is the advancement version of early type pulse generator which used vacuum tubes. With advancement of electronics, solid-state devices such as transistor replaced the vacuum tubes. Transistor acts like an electronic switch that can be opened or closed depending on the electronic signal from the switch. When closed, the transistor makes a close loop circuit which allows electricity to flow from the DC

power supply to the electrode, across the workpiece through sparks, and thus create the 'on' state. When the switch is opened, transistor blocks the flow of electricity from the DC power supply and results in an 'off' state of the input pulse. The 'on' and 'off' states of transistor type pulse generator are set in EDM power supply control, either manually or computer assisted.

Figure 2-6 Schematic of EDM pulse generator (a) RC type (b) Transistor type

Transistor based pulse generator is widely used in conventional EDM. This type of pulse generator produces pulse discharges using an on-off switching component; therefore it allows the user to control the discharge duration easily. As a result, a high pulse frequency and high removal rate can be obtained. However, due to the delay transmission of switching component, this type of power supply cannot provide a very short pulse on time, in the order of sub microseconds, as needed in micro-EDM. In micro-EDM, the material removal per pulse should be extremely small, thus it requires minimization of the pulse energy supplied into the gap. Minimization of the pulse energy can be easily obtained using a RC type pulse generator which is able to produce a very short pulse duration. This characteristic makes R-C type pulse generator is commonly used for micro EDM. However due to the time needed to charge the capacitor, it cannot produce a high frequency pulse and furthermore the pulse interval cannot be controlled.

Recent electronics advancement has brought EDM pulse generator to the next level. A transistor type isopulse generator for micro EDM has been developed by Fuzhu Han *et*

al. [32, 33]. It is reported that the isopulse generator was able to reduce the pulse duration to 30 ns which is ideal for finishing by micro EDM machining

2.2.2.2 Servo System

EDM process does not continue indefinitely as sparking increases the electrode-workpiece gap distance. Therefore a servo system is needed to ensure continuous machining process to occur by feeding the electrode toward the workpiece while maintaining a proper gap distance. Servo system provides an automatic operation to maintain the gap voltage and avoid destructive discharges. It employs the measured average voltage across the gap and compares it with an adjustable servo reference voltage. The servo reference voltage is usually set at a certain range within the range of discharge voltage. To maintain the average gap voltage in a certain value, common EDM servo system usually follows the following procedure:

- It advances the electrode towards the workpiece when the measured average machining voltage is above servo reference voltage range
- It holds the electrode position stationary when the measured average machining voltage is within servo reference voltage range
- It retracts the electrode from the workpiece when the measured average machining voltage is below servo reference voltage range

The procedure above is called as ‘normal machining method’ in this work. Selecting the optimum range of servo reference voltage is important to keep the process running in an appropriate manner. Different dielectric properties, electrode materials, or machining settings will give different value of optimum reference voltage range. So far, the selection of reference voltage range is dependent on the experience and skill of the EDM operator. To overcome with this problem, several research works have been done to develop adaptive servo control system for EDM.

Kruth *et al.* developed an adaptive control system which automatically searches for machining settings coinciding with optimal working conditions [34]. Servo reference voltage, pulse off time and dielectric flushing flow rate were optimized during the process (on-line) while other parameters were optimized prior to the process (off-line). EDM fuzzy logic servo control system was developed by Boccadoro *et al.* for die sinking process [35]. The developed system was able to optimize spark parameters (pulse on time, pulse off

time, current, open voltage, flushing and servo reference voltage) by utilizing fuzzy logic rules in order to maximize the machining speed. Furthermore the use of unfixed fuzzy rules, known as self-adjusting fuzzy control, for improving machining performance has been investigated by Kaneko [36]. The adaptive controls using fuzzy logic control strategy have also been implemented in WEDM [37-39]. Other type of adaptive control system in die sinking EDM is self-tuning adaptive auto jumping control system [40, 41]. This system regulates the jump-down-time at an optimum level which varies according to the gap condition.

2.2.2.3 Electrode and Workpiece

The main advantage of EDM process is the ability to machine high-complexity shapes regardless of the mechanical properties of the material such as hardness, brittleness, and toughness. However the restriction for EDM work material is also clear, it has to be electrically conductive. EDM has been widely used for machining hard material such as: steel with various types and compositions [42-45], titanium and its alloy [46, 47], and aluminium alloys [48, 49]. In early 1980s, EDM has been brought to play in advance ceramics machining [50]. It is reported that ceramics can be classified into non-conductor, natural-conductor and conductor and the only requirement to be applied in EDM process is that the electrical conductivity is over 0.01 S/cm [51]. Several research work have attempted to use ceramic based material as EDM work material such as; boron carbide (B_4C), reaction bonded silicon carbide ($SiSiC$) [52], cobalt-tungsten carbide ($WC-Co$) [53], Zirconia Ceramics (ZrO_2) [54], Silicon Nitride (Si_3N_4) and Aluminium Oxide (Al_2O_3) doped with TiC [55]. EDM has also been used extensively in composite material [56, 57].

Similar to work material, tool electrode materials must also be electrically conductive. Ideal electrode materials should have a high melting point, an ability to be easily machined and a low tool production cost. However there is no single electrode material that can provide these ideal behaviors for any particular application. The commonly used electrode materials in industry nowadays are brass, copper, copper tungsten, graphite, copper, graphite, zinc alloys, and carbon. The main concern of tool electrode material is always about the tool wear occurrence. Comparison of the tool wear ratio (TWR) for machining hardened tool steel (En-31) using different electrode materials is shown in Figure 2-7 [58].

Several research work have attempted to utilize composite material such as ZrB₂-Cu [59] and Cr-Cu [60] as EDM tool electrode to get an optimum combination of high wear resistance, and high material removal rate ability. Diamond materials have also been evaluated as an exotic EDM electrode material. It is reported that the use of polycrystalline diamond (PCD) and boron doped CVD diamond (B-CVD) provides a low relative tool wear as compared to common materials such as graphite, copper and tungsten copper [9].

Figure 2-7 Variation of electrode wear for different electrode materials [58]

2.2.2.4 Dielectric fluid

Fluids are normally used as dielectric medium since they provide a controllable environment to surround the sparking area. EDM dielectric fluid is defined as an electrical insulator that resists the flow of the electricity, until the voltage, high enough to cause the fluid to change into an electrical conductor, is applied [13]. Dielectric fluids perform some important roles in sparking process as follows:

- As an electrical barrier between electrode and workpiece
- As a cooling agent for electrode and workpiece
- As a cooling agent for vaporized materials and turns them into EDM chip upon solidification
- As a debris flushing agent

Most commonly used EDM dielectric fluids are hydrocarbon fluids and deionized water. The desired properties for dielectric fluid are: low viscosity as it helps fluid flows more readily to flush the spark gap and high flashing point to avoid possibility of fire ignition. Properties of dielectric fluids affect the machining performance as they provide the discharging condition in the spark gap. Therefore selection of EDM dielectric fluid is essential in EDM process. The influence of kerosene and distilled water on the material removal rate (MRR) and tool wear ratio (TWR) is shown in Figure 2-8.

Figure 2-8 Influence of kerosene and distilled water on MRR and TWR [61]

Aside from kerosene and distilled water [61, 62], several research work have attempted to utilize different types of fluid such as water [63, 64], water with urea solution [65], and powder mixed dielectric. The use of powder mixed dielectric has been studied since 1980 and since then many investigations have been conducted on various type of powder. The powder mixed dielectric provides an ability to improve the overall EDM machining performances [66-71]. Attempts to use non-liquid medium as dielectric for EDM process, known as dry EDM process, have also been investigated [72, 73].

2.2.3 EDM Parameters

EDM parameters can be divided into process parameters and performance parameters. Process parameters are input variables which affect the outcome of the EDM process while performance parameters are quality descriptions for an EDM process. Constructing a

reliable relationship between process parameters and performance parameters has become a major research interest.

2.2.3.1 Process Parameter

The selection of process parameters in EDM was traditionally based on handbook values from EDM machine manufacturers. These data handbook are usually collections of experiences from EDM operators and experts. Figure 2-9 shows a typical conventional EDM waveform together with its nomenclature.

Figure 2-9 Nomenclature of EDM waveform

The following are the common process parameters used in EDM:

- Pulse on time (T_{on})

Pulse on time is the time duration when sparking occurs. It begins when the voltage drops to its ionized state and current starts to flow. It is ended when the electricity supply is cut off causing voltage drops to zero and current stops to flow. The longer the pulse on time, the higher MRR, TWR and Surface Roughness (SR) obtained in the process.

- Pulse off time (T_{off})

Pulse off time is the interval time between two successive sparks. It starts at the end of the previous pulse on time and ends at the next dielectric breakdown. The main

function of this parameter is to ensure that dielectric has enough time to regain its insulating strength in order to avoid arcing.

- Delay time (T_d)

Delay time is a measure of time which begins when the voltage has retained open circuit voltage value until the dielectric breakdown occurs. Delay time is an important parameter in monitoring system to distinguish sparking and arcing.

- Open circuit voltage (V_{oc})

Open circuit voltage is the amount of voltage supplied by the DC power generator. It has a direct impact of increasing the discharge energy inside the gap as well as to increase MRR, TWR, and SR

- Discharge voltage (V_d)

Discharge voltage is the constant value of voltage occurs during plasma channel expansion. This parameter is uncontrollable and strongly influenced by the property of the dielectric.

- Peak Current (I_p)

Peak current is the maximum amount of current takes place during pulse on time. This parameter can be directly controlled in conventional EDM. In the case of micro EDM, peak current is indirectly determined by the value of capacitor setting being used.

- Polarity

Polarity is the positive and negative sign of the electrode and workpiece. It determines the direction of electrons and positive ions flow. Commonly, polarity nomenclature specifies only the electrode sign. Conventional EDM usually uses positive polarity whilst micro EDM usually uses negative polarity. In general, the effect of polarity to the erosion rate is shown in Figure 2-10. For large pulse on-time the erosion rate for anode is almost negligible as compared to cathode [74]. Negative polarity is also reported to give a significant rise to electrode wear as compared to positive polarity [8].

Figure 2-10 Erosion rate for cathode and anode for different pulse on time [74]

2.2.3.2 Performance Parameter

EDM process performance is usually evaluated by three parameters: Material Removal Rate (MRR), Tool Wear Ratio (TWR), and Surface Roughness (SR).

- Material Removal Rate (MRR)

MRR is defined as the volume of material removed from the workpiece during the machining time.

- Tool Wear Ratio (TWR)

TWR is defined as the ratio between volume of material removed from the electrode and volume of material removed from the workpiece. This parameter represents the severity of wear during the EDM process.

- Surface Roughness (SR)

In general term, roughness is defined as irregularities inherent in the production process left by the machining agent such as cutting, tearing, and surface fatigue. Surface roughness in EDM is usually represented in roughness average (R_a) which is defined as the arithmetic mean of the departure of profile from a mean line.

An ideal EDM process should provide a high MRR value with low TWR value while maintaining SR at the required value at the same time. EDM is a stochastic process which influenced by electrical process parameters and non electrical process parameters. Constructing a direct relation between process parameters with process performances has become the main challenge in EDM. Empirical relationship using a set of Design Of

Experiments (DOE) method has been developed to approximate MRR and TWR with several electrical parameters as the input parameter. This method has been applied for silicon carbide [75] and cemented carbide [53] material. A similar approach is done using Taguchi's DOE and analysis of variance (ANOVA) for $\text{Al}_2\text{O}_3/6061\text{Al}$ [56] and copper-steel material [76]. It is reported that electrical parameters affect the machining characteristics more significantly than non-electrical parameters. Wang and Tsai presented a semi empirical model of material removal rate for various workpiece and tool electrode combinations [77]. The effect of process parameters to surface roughness has also been investigated with a similar approach [43, 49, 78]. It was concluded by Guu *et al.* that maximizing MRR while maintaining TWR along with improving surface roughness, cannot be achieved simultaneously with a particular combination of control parameter settings [79]. As there is no single combination of parameters which provides the best machining performance, optimization technique is needed to resolve this problem. The rapid development of computing technology has brought solution by introducing neuro-fuzzy network model [80] and artificial neural network (ANN) [81-83] to predict and provide the optimum machining performance.

2.2.4 Application of EDM in micromachining

A miniaturized scale of EDM process is known as micro EDM. The term micro is used since the resulting product is in range of several microns to several hundred microns. The basic working principle, configuration and parameters of micro EDM is similar with conventional EDM. Micro EDM also inherits conventional EDM unique characteristics and advantages which make it popular in micromachining of metallic material. Basically micro EDM can be developed from conventional EDM machine by reducing the discharge energy, utilizing small electrode size, and improving the positional accuracy. The differences between common conventional EDM and micro EDM are presented in Table 2-1. The difference of crater size between conventional EDM and micro EDM is explicitly shown in Figure 2-11 [84].

Figure 2-11 Comparison between crater dimension in conventional (left) and micro EDM (right) [84]

Table 2-1 Differences between conventional EDM and micro EDM

Factor	Conventional / Macro EDM	Micro EDM
Pulse generator	Transistor based pulse generator	Resistor-Capacitor (RC) type pulse generator
Polarity	Workpiece negative polarity Electrode positive polarity	Workpiece positive polarity Electrode negative polarity
Pulse on time	Large pulse on time ($> 1 \mu\text{s}$)	In sub micron second range
Discharge energy	High ($> 10^{-7}$ Joule)	Low ($10^{-6} - 10^{-7}$ Joule) [1]
Gap distance	High gap distance ($> 10 \mu\text{m}$) [28]	Small gap distance between $1.5 - 5 \mu\text{m}$ [84]
MRR	High	Low
Controllable parameter	Open Circuit Voltage Pulse on time Pulse off time Peak Current Electrode rotation (rpm) Dielectric flushing pressure	Open Circuit Voltage Resistor Setting Capacitor Setting Electrode rotation (rpm)
Electrode size	Big ($> 1 \text{ mm}$)	Small ($< 1 \text{ mm}$)
Others	The requirement of tool (electrode) precision and the clamping system (repeat accuracy) is not as high as micro EDM	The requirement of tool (electrode) precision and the clamping system (repeat accuracy) is very high ($\sim 1 \mu\text{m}$)

Micro EDM is suitable for producing small feature with high aspect ratio. Micro rod as small as $2.8 \mu\text{m}$ diameter has been achieved by Han *et al.* [85]. Since the working principle is similar, micro EDM can also be used for other variance of EDM operations such as micro EDM drilling, Micro EDM die sinking, micro EDM milling, micro wire EDM (WEDM), and micro wire electrical discharge grinding (micro WEDG). The overview of micro EDM variant capability is provided in Table 2-2. The main advantage of micro

EDM process as compared to other micro machining technique is its capability to produce complex shape of 3D microparts. This capability is fully demonstrated in Figure 2-12 where (a) a complex micro cavity was machined using micro EDM milling [84] and (b) complex 3D micro Chinese pagoda was fabricated using micro WEDM [86].

Figure 2-12(a) Microcavity made by micro EDM milling [84] (b) micro chinese pagoda made by micro WEDM [86]

Table 2-2 Overview of micro EDM capability [1]

Micro EDM Variant	Geometry Complexity	Minimum Feature Size	Maximum Aspect Ratio	Surface Roughness Ra (μm)
Micro EDM Drilling	2 D	5 μm	~ 25	0.05 - 0.3
Micro EDM Die Sinking	3 D	~ 20 μm	~ 15	0.05 - 0.3
Micro EDM Milling	3 D	~ 20 μm	~ 10	0.5 – 1
Micro WEDM	2 ½ D	~ 30 μm	~ 100	0.1 – 0.2
Micro WEDG	Axi-sym	3 μm	~ 30	0.8

2.3 Specific Technological Advances in EDM

This section focuses on specific technological advances and current trend in EDM to give a better understanding and knowledge for developing a reliable real time tool wear compensation system. The review includes anode-cathode erosion model, the pulse discriminating system, tool wear phenomenon and comparison of available tool wear compensation systems.

2.3.1 Review on Anode-Cathode Erosion Model

The schematic of EDM model is shown in Figure 2-13. During sparking, EDM input energy is distributed in three regions, namely the plasma channel formation [87], the anode

erosion [88] and the cathode erosion [74]. Understanding the anode and cathode erosion model would help to give a better perceptiveness on the material removal mechanism.

There are two approaches in modeling electrode erosion in EDM process: the electro-mechanical model [89] and the electro-thermal models [74, 88, 90-96]. Electro-mechanical model suggests that the electrostatic forces are the major cause of metal removal for short pulses. The high electric field separates the material particles of the electrodes when the cohesion forces in the lattice of the material are exceeded. In the electro-thermal model, the material removal occurs due to melting process by extremely high temperatures. The extreme temperature is generated by the electric current which flows through the plasma channel. This model has been supported by several experimental evidences and reported since 1971 [91].

Figure 2-13 Schematic of EDM model [96].

Electro thermal models are based on thermal conduction principle which uses the following general assumptions:

- Only one spark occurs for one discharge
- Heat impinging to electrode surface is dissipated only by conduction. Radiation and convection heat losses are negligible.
- Shape of heat source is known and defined
- Heat flux from the source is known and defined

- Thermo-physical properties of the electrode materials are independent of temperature
- The heat source is active for a known finite interval of time
- The electrode surfaces are completely insulated except for the portion where the heat source is acting.
- Electrode is considered a semi-infinite body since the volume of material removed is much smaller compared to electrode's volume

Apart from the main assumptions being used, additional specific assumptions are also introduced to the model. Various researchers have reported different specific assumptions in order to provide the best approximation with the experimental result. These specific assumptions include: the shape of heat source at anode and cathode, heat source radius, heat flux intensity profile, fraction of energy to electrodes and plasma channel, and range of discharge energy covered. A critical assessment of several electro thermal models has been undertaken by Yeo *et al.* where the main differences between the models are summarized in table 2-3 [97]. In this comparative assessment, Yeo *et al.* concludes that Dibitonto's model [1989] which assumes a point heat source for cathode erosion provides a better agreement with experimental data as compared to other models (Snoeys and Van Dijck [1971], Van Dijck and Dutre, [1974], Beck [1981], Jilani and Pandey [1982-1986]) especially at high discharge energy regime. Furthermore the simplicity of its equation provides a fast computational time with adequate accuracy. However, Yeo *et al.* also reveals the potential of disk heat source model to be developed further by incorporating a better approximation of heat flux radius and fraction of energy

Discharge energy, discharge current and pulse on-time considered by most models are in conventional EDM regime. Attempt to bring the electro-thermal model in micro EDM regime is given by Yeo *et al.* [96] where the discharge energy is in the range of $5\mu\text{J} \sim 150\mu\text{J}$, and pulse on time is in nanosecond regime.

In the electro thermal model, it is obvious that the resulting crater dimension is affected by the discharge energy and thermal properties of electrodes. Material erosion unavoidably occurs at both electrodes. Consequently tool wear phenomenon is inevitable. Tool wear can only be minimized by employing electrode materials with high thermal properties.

Assumptions	Snoeys's model (Snoeys and Van Dijk, 1971)	Van Dijk's model (Van Dijk and Dutre, 1974)	Beck's model (Beck, 1981a,b)	Jilani's model (Jilani and Pandey, 1983, 1982; Pandey and Jilani, 1986)	DiBitonto's model (DiBitonto et al., 1989)
	Upper part of electrode is adiabatic	Upper part of electrode is adiabatic	Surfaces beyond the disk region are insulated	Uniform heat flux with constant radius	Heat flux from a point heat source Effective (average) thermophysical properties of the material over the whole temperature range from solid to liquid melt
	Constant thermophysical properties of the material over the whole temperature range Erosion takes place in molten area of an electrode Constant heat flux	Constant thermophysical properties of the material over the whole temperature range Erosion takes place in molten area of an electrode Constant heat flux	Constant thermophysical properties of the material over the whole temperature range Erosion takes place in molten area of an electrode Constant heat flux	Constant thermophysical properties of the material over the whole temperature range Erosion takes place in molten area of an electrode Plasma channel is expanding with time	Erosion takes place in molten area of an electrode The plasma radius remains small during the discharge One-dimensional heat flow Point heat source
Main features	Two-dimensional heat flow Semi-infinite cylinder with circular heat source	Two-dimensional heat flow Finite cylinder with circular heat source on the surface	Two-dimensional heat flow Semi-infinite cylinder heated over a disk-shaped region	Two-dimensional heat flow Semi-infinite body with a disk heat source on the surface	
Fraction of discharge energy Radius of the heat flux Limitation	50% Constant (r_c) Approximation of heat flux radius is not readily available Effects of vaporization is neglected	50% Constant (r_c) Approximation of heat flux radius is not readily available The number of terms used highly affect the results	50% Constant (r_c) Direct application of a disk heat source	50% Expanding with time The effect of vaporization is neglected	18% Not applicable The crater profile resulted is hemi-spherical
	Guideline for the outer cylinder radius value is not available	No guideline for the determination of the electrode thickness	Approximation of heat flux radius is not available Effects of melting heat is neglected	Guideline for the outer cylinder radius value is not available	Large heat flux radius as compared to crater radius occurs in small pulse on-time Effects of vaporization and melting heat is neglected

Figure 2-14. Summary of EDM models [97]

2.3.2 Pulse Discrimination and analysis in EDM Process

Real time monitoring system is required to provide certain automation system for improving process productivity. Normally, voltage and current waveforms are used to monitor EDM process. They are sensitive to process alteration which involves complex, stochastic and time-varying characteristics. Advanced monitoring systems are used to classify various EDM pulses in order to provide more valuable information.

2.3.2.1 Pulse Classification

The ideal discharge voltage and current waveforms are shown in Figure 2-9. However during the process, they vary as the gap condition changes. Possible variations of voltage and current waveform in conventional EDM are shown in Figure 2-15.

Figure 2-15 Different Pulses in Conventional EDM Process

EDM process essentially has a strong stochastic characteristic; noisy gap voltage and current signal with some degree of uncertainty and vagueness are unavoidable. As a result, researchers derive effective ways to discriminate EDM pulses. Generally the conventional EDM pulses can be classified as follows:

(a) Open Circuit Voltage pulse (Figure 2-15(a))

Open circuit voltage describes the condition when the pulse generator is turned on but the electrode-workpiece gap distance is not close enough to initiate any discharges. This pulse usually occurs during the initial stage when the electrode is still traversing towards the workpiece to find the initial discharge gap. This pulse is not considered as a discharge pulse.

(b) Normal discharge pulse (Figure 2-15(b-d))

Normal discharge pulse is the desired discharge pulse, which normally contributes most for the material removal process. It is randomly distributed along the eroding surface indicating that the degree of contamination in the gap is low. It is identified as a pulse with ignition time delay. Time delay is the time when the voltage remains at the open circuit voltage. Normal discharges usually have variation in their delay time as shown in Figure 2-15(b-d). They are usually presented as percentage of pulse duration time. For example Figure 2-15(d) is a discharge with time delay longer than half of the pulse duration, and sometimes it is labeled as delayed discharge. Cogun reported that discharges with short delay time are mainly responsible for material removal, and they are found to have higher material removal rates per unit discharge time [98]. In contrary, discharges with long delay time have been reported to have an insignificant effect on material removal [99]. Discharges with very long time delay will result in shorter pulses, and consequently giving rise to arcs, shorts, and instability of the operation. For maximum workpiece removal rate and low relative wear, number of discharges with short time delay should be kept at maximum [98].

(c) Arcing pulse (Figure 2-15(e-f))

Arcing is defined as succeeding discharges which occur at the same physical location on the electrode surface. The term “arcing” is granted since it has essentially the same destructive effect on the workpiece as a long duration of arc although the current waveform comprises discrete pulses. Arcing can be identified from the pulse waveform when discharge occurs although the voltage has not returned to its open circuit voltage value from the previous spark. It indicates that the dielectric has not fully deionized and the insulating strength cannot be achieved. Therefore, there is a high probability that the following sparks will take place at the same physical location. This repetitive sparks at the same location can destroy the surface finish of the workpiece due to accumulative heating effect and may further need an expensive re-finishing process such as diamond finishing. Bartel and Hockenberry have investigated the destructive effect of arcing and describe that it can take two forms [100]:

- Coking

Coking phenomenon is the worst condition that can occur due to its damage is usually non-repairable. The concentrated discharges cause the growth of carbon on the surface of the electrode and workpiece. The label of “coking” is given by

EDM machine operators owing to the similarity of the carbon growth to coke. A small piece of the carbon growth can initiate other coking formation to grow and form in different sizes. Once the carbon growths appear they cannot be easily get rid of, and the most effective way is to interrupt the machining process and eliminate them manually. Coking usually originates at the edge of electrode machining surface where the contamination level is high.

- Burring

Burring refers to the rough burred appearance at the leading edge of the machined cavities. Burring is usually less severe than coking; however it usually needs expensive hand finish to salvage the workpiece. In severe case of burring, workpiece may be destroyed.

A more precise investigation and analysis on discharge types has been reported by Dauw *et al.* [101], and it was found that arc discharge can be classified further into “effective arcs” and “non effective arcs”. Some types (arc pulses which have a normal discharge characteristic) contribute to workpiece material removal whereas others have a strong correlation with tool material removal.

Arcing is well recognized by machine operators and researchers as one of harmful discharges. Once arcing occurs, special action needs to be taken to avoid continuous destruction. A common way is to retract the electrode to recover the flushing condition and allows dielectric to regain its insulation strength.

(d) Short circuit pulse (Figure 2-15(g))

Short circuit happens when there is a metal to metal connection between the tool and work-material and it results in no material removal. It is often represented as the condition where tool electrode touches the workpiece. Short circuit is unwanted and special action is needed once it occurs to prevent electrode breakages. It is indicated when the current is flowing while the voltage remains zero.

(e) Off pulse (Figure 2-15(h))

Off pulse is an indication when pulse generator is turned off.

2.3.2.2 Review on pulse discriminating system

As described in the preceding section, it is obvious that there are certain pulses to be avoided to ensure the machining process runs smoothly, and avoid surface destruction at the workpiece. However, up till now, detection of unwanted discharges in EDM is still based on operator's experiences and uses some indistinct parameters such as: if the sparking noise becomes quiet and smooth without normal snapping and crackling or if the EDM smoke change from gray to white, which means that arcing may have started [13]. To deal with this problem, many researchers have developed a pulse discrimination system.

The simplest discriminating method is done by comparing gap voltage with preset voltage threshold at a predetermined time [102, 103]. The voltage threshold value was carefully defined from experimental observations, and sometimes judgement of current in the gap is also used [103]. The flowchart of this method is presented in Figure 2-16. Voltage thresholds ($V_1 - V_4$) are defined to identify the voltage condition and classify EDM pulses. With consideration of the strong disturbances in sampled waveforms, there is also a threshold I_d set for judging the existence of current in the gap. I_d is used in the pulse classification process.

Figure 2-16 Flowchart for discriminating the gap state at the sampling time [103]

Several pulse discriminating (PD) systems have been developed by various researchers based on various parameters. Snoeys and Cornellissen utilized ignition delay time to

distinguish normal discharge and harmful arc [104]. Pulses following an ignition delay were considered as normal discharge, whereas discharges without ignition delay were categorized as harmful arc. Furthermore, a combination of ignition delay time and voltage fall time was used as a differentiating parameter by Weck [105]. Voltage peak value discovered by a real-time peak detection algorithm was used to classify the pulses into normal, stable arc, unstable arc, and short circuit [106]. A more detailed pulse differentiating system was developed by Dauw *et al.* [101]. They generally categorized discharge pulses into 7 types and specifically distinguished them into 15 types based on ignition delay time, fall time, and discharge voltage. Furthermore, the same authors suggested that an effective spark should have a short rise time up to the generator open voltage level, an ignition delay time greater than 200 ns, a pulse fall time between defined limits, and the discharge voltage must be within a pre-determined voltage range [107]. Watanabe *et al.* used statistical approach to classify WEDM pulses for offline process optimization [108]. Rajurkar *et al.* used a data-dependent-system (DDS) technique to describe the EDM voltage and current signal, and they provided a discriminating frequency for sparking and arcing [109].

Another work is carried out utilizing the rapid advancement of computing technology to differentiate gap pulses. Tarng *et al.* developed a fuzzy pulse discriminator based on a set of fuzzy rule from the gap voltage and current waveform's characteristics [110]. A neural network approach for monitoring EDM process was developed by Kao [111]. It used three layers of artificial neuron to evaluate the gap pulses. A different approach for monitoring EDM process was done by Rajurkar *et al.* Instead of observing the gap voltage, they exploited the radio frequency (R.F) signal emitted during EDM and used it to distinguish sparking and arcing [112]. It is reported that R.F signal will fall as the discharge moves from sparking to arcing.

As described above, a number of pulse discriminating systems have been developed, but none so far is applicable for micro EDM since it generally uses RC type pulse generator which has different waveform characteristic as compared to the conventional EDM waveform. Furthermore micro EDM minimizes discharge energy which results in a very short pulse duration (in sub micro second regime); thus more accurate monitoring system is needed, and data acquisition systems with high sampling rate must be employed. An initial attempt to differentiate micro EDM pulses has been done by Liao *et al.* [113]. In

their work, micro EDM pulses are classified as normal, effective arc, temporary short and complex pulse. However the average gap voltage criteria is still taken for servo feed control for micro-EDM and micro WEDM up till now [86]. A more reliable and comprehensive real time pulse discriminating system is needed as the basic structure for real time monitoring system of micro EDM process.

2.3.3 Tool Wear Phenomenon in EDM Process

Tool wear phenomenon in EDM is a very critical issue since the tool shape degradation directly affects the final shape of the machined feature. This problem becomes more important in micro EDM since the negative polarity makes the tool wear more severe.

2.3.3.1 Geometry of EDM tool wear

The geometry of a tool wear is shown in Figure 2-17. Generally tool wear in EDM can be categorized into:

(a) Side Wear

Side wear is represented as tool side surface taper angle, β in Figure 2-17. This wear is generated by the discharges between the tool and the escaping debris or by the tool and side of the workpiece. An insulating sheath at the side of the tool was introduced by Kumagai *et al.* to overcome the side wear problem [114]. For drilling shallow hole or milling layer by layer, side wear can be neglected. In many research work, side wear is ignored since it normally has a very small angle and the amount is negligible.

(b) Corner wear

Corner wear is the wear which forms a rounded arc of circle at the edge of the tool. It is described as arc A-B and C-D in Figure 2-17. Sometimes, corner wear is also described as the vertical length difference between A-B or C-D. This wear deteriorates the shape quality of the resulting machined feature. Corner wear occurs at the beginning of the machining process and takes place at much higher rate than longitudinal wear. On the investigation using on-machine measurement system, it is observed that corner wear is several hundred times faster than longitudinal wear at the beginning of machining time [115]. At the first 100 minute of machining time, the corner wear increases as much as 100 μm whereas longitudinal wear is only increased by 20 μm .

(c) Longitudinal wear

Longitudinal wear is easily expressed as the difference between electrode length before and after machining. It is represented as ΔL in Figure 2-17. Longitudinal wear directly reduce the accuracy of the machined feature unless an appropriate tool wear compensation method is implemented.

(d) Volumetric tool wear

Volumetric tool wear is the difference between electrode's volume prior to machining with the volume upon completion of machining. It is a summation of the side wear, corner wear and longitudinal wear. This parameter is the most commonly used parameter for studying and analyzing tool wear in EDM process. In conventional EDM, volumetric wear can be determined by comparing the weight of electrode before and after machining and then multiply it with the density of electrode material. However for micro EDM, this method is not reliable due to the small mass of the electrode being used, even if an ultra precision scale is employed. Geometrical measurement is a preferred method to measure the volumetric tool wear in micro EDM. Simplification of worn electrode shape as a cylinder is the simplest way to calculate the volumetric wear [116]; however this method does not consider the corner wear occurs in the process. An accurate and reliable tool wear measurement process was carried out by Yan *et al.* using machine vision system [117]. The drawback of this method is the high cost for developing such a complex measurement system. Another approach for tool wear measurement in micro EDM could be done by mapping the electrode before and after machining and uses a software program to calculate the worn material. The accuracy of this method will depend on the accuracy of the mapping method, and the ability of the software to reconstruct the measured profile. This method will be used in this research work.

Figure 2-17 Geometry of a tool wear in EDM process

2.3.3.2 Corner wear phenomenon in EDM process

The occurrence of corner wear during machining is an interesting phenomenon which can be explained by the following factors:

(a) Electric field intensity

The electric field intensity depends upon the voltage difference between the electrodes (ΔV), the size of the gap (g), and the shape of the active surface of the electrodes as presented in the following equation [118].

$$K_E = \frac{\Delta V}{g} K_\beta \quad (2.1)$$

where K_β is the non-uniformity coefficient of the electric field which depends on the dihedral angle. K_β decreases as dihedral angle increases.

The shape and structure of the electrode surface create non-uniform electric field and initiate high frequency of local discharges to occur at the location with the highest electric field intensity. For cylindrical electrode, the highest electric field takes place at the surface which is perpendicular to the feed, since the current density reaches maximum when the dihedral angle attains 90° . Ivanov *et al.* simulated the electric field intensity inside the gap using finite element software [119]. It is observed that at first, the electric intensity attains maximum value at the corner edge and then shifted toward

the centre with the rounding edge of the cylindrical electrode and finally form uniform field intensity with rounding electrode shape as illustrated in Figure 2-18(e).

This simulation explained the constant shape of the hole/electrode observed by Pham *et al.* [120] when they drilled hole with depth higher than 180 μm . After a certain depth, the electrode continues to wear but its shape remains the same. However this trend was only observed visually without any reliable measurement conducted. Furthermore the occurrence of this trend for various machining setting and electrode material variation is still left questionable.

Figure 2-18 Simulation of electric field intensity inside the gap, adopted from [119].

Figure 2-19 Constant electrode shape attained during micro EDM drilling [120]

(b) Precipitation of carbon layer at electrode surface

During EDM process, both tool and workpiece suffer surface modification as there will be migration of workpiece elements to the tool surface. Mohri *et al.* [115, 121] observed a layer of carbon adhered to the electrode surface during machining of carbon steel using copper electrode. Some of the molten material, expelled from the workpiece during the collapse of the plasma channel, moves to the electrode together with the cracked carbon from dielectric oil. This workpiece material-carbon solution is attached on the electrode surface and it precipitates as turbostratic¹ carbon on the electrode surface following the temperature drops. The attached workpiece metal acts as a catalyst for the precipitation of crystallized carbon. This carbon layer protects the electrode from wear erosion. The same observation was also found by Marafona where the microstructure photograph of this layer, namely black layer, is shown in Figure 2-20 [122]. Further investigation by Marafona showed that the electrode wear ratio decreases with the increase of the carbon composition at black layer as presented in Figure 2-21 [123]. The amount of carbon composition increases according to the increase of pulse duration. The corner wear at tool electrode happens since the carbon cannot precipitate at the region with large curvature [115].

¹ A type of crystalline structure where the basal planes have slipped sideways relative to each other, causing the spacing between planes to be greater than ideal.

Figure 2-20 View of black carbon layer above tool electrode [122]

Figure 2-21 The trend of carbon composition and EWR [123]

2.3.3.3 Factors affecting tool wear in EDM

Many factors affect the tool wear rate and tool wear ratio during the machining process. The effects of electrical process parameters to electrode wear in EDM process are summarized and presented in Table 2-3. The term ‘positive effect’ in Table 2-3 means that the increase of the parameter concerned will result in the increase of the amount of tool wear whereas for ‘negative effect’, the situation is vice versa.

It is observed that an increase in discharge energy value will result in lower TWR value for micro EDM [124]. In RC type pulse generator, increasing discharge energy can be achieved by either increasing capacitor or open circuit voltage value. Interestingly, the same discharge energy value from different capacitor-voltage combination will result in different TWR value [124]. Higher capacitor setting will attribute to higher pulse interval which gives less probability of arcing and instability of machining process to occur.

Therefore in order to achieve higher discharge energy, increasing capacitance is more preferred than increasing open circuit voltage.

Table 2-3 Effect of electrical process parameter toward tool wear in conventional EDM

Parameter	Effect	Remarks
Discharge/peak current	Negative effect at short discharge current regime ($<5A$) [125]	High peak current will result in higher discharge energy and the resulting single crater size
	Positive effect at medium and high discharge current regime ($>5A$) [10, 126]	
Open Circuit Voltage	Positive effect throughout the whole regime [10, 125, 126]	At low voltage regime ($<80V$), increase in voltage will only result in slight increase of TWR, the positive effect of voltage is increased at high regime ($>80V$)
Pulse ON-time	Positive effect at short pulse duration regime ($<25\mu s$) [10, 126]	At long pulse duration, the black carbon layer is attached to electrode surface and enhances the wear resistance of the tool electrode.
	Negative effect at high pulse duration regime ($>25\mu s$) [10, 115, 125]	
Pulse OFF-time	Negative effect at short pulse off time regime ($<100\mu s$) [126]	Although short pulse off time favors removal rate and tool wear, it is not suitable with high discharge currents. When the resulting high concentration of debris is inadequately flushed out, it will lead to arcing and instability.
	Positive effect at long pulse off time regime ($>100\mu s$) [126]	
Polarity	Negative tool polarity gives lower TWR than positive polarity at low to medium discharge current value [10, 124, 126]	For positive polarity TWR decreases significantly with the increasing current. TWR does not vary significantly at high current for both polarities.

The effect of non-electrical process parameter on the TWR is described as follow:

(a) Electrode material

In principle, electrode material for EDM process should have a high melting point and low resistance to electricity. However a specific electrode material performs diverse degree of success of process performances (MRR, TWR, and SR) on different workpiece materials. Therefore, selection of electrode material depends on the specific cutting application. Nevertheless for TWR performance, it is generally found that electrode wear is inversely proportional to melting point of the electrode [126]. In

comparison of several electrode materials for machining tungsten carbide, it is found that material with the highest melting temperature achieves the smallest amount of tool wear for the whole range of peak current setting [126].

In micro EDM, Tsai and Masuzawa proposed boiling point as an important parameter to evaluate erosion property of tool material [127]. Furthermore it was observed that corner wear is more severe and obvious for material with low thermal conductivity. Corner wear of electrode relates closely to the diffusion of heat. The ideal properties of electrode material to perform a low TWR value are: high boiling point, high melting point, and high thermal conductivity.

(b) Electrode Geometry

TWR increases as the electrode diameter decreases regardless of the electrode material being used [124, 127]. The reduction in size leads to the decrease of heat flow in solid and results in higher melting and tool wear for smaller diameter tool electrodes [124]. This trend is valid for both conventional and micro EDM.

(c) Dielectric fluid

The common dielectric fluids used in EDM process are kerosene and distilled water. In a study to compare these two dielectrics, it is observed that distilled water offers lower TWR value than kerosene for machining Ti-6Al-4V [61]. Experimental investigation performed by König also showed that kerosene provides lower TWR value as compared to other aqueous solutions of organic compounds [128].

(d) Dielectric flushing pressure

The increase of dielectric pressure at low-pressure setting results in a significant increase in TWR whereas the increase of pressure at high dielectric pressure settings insignificantly affects TWR [126, 129]. At low dielectric pressure setting, the flushing cannot remove the gaseous and solid debris after each discharge which results in unstable machining conditions and arcing at the region with high concentration of debris. When dielectric pressure reaches a point where the pressure is adequate to produce a proper flushing, an increase in flushing pressure gives insignificant effect to the TWR.

2.3.4 Tool Wear Compensation System

For accurate machining, the tool wear compensation system needs to be embedded inside the EDM control system, especially in milling layer by layer process where tool wear directly deteriorates the accuracy of the product. Available tool wear compensation methods for EDM process can be categorized into:

- Multiple electrode method [130, 131]
- Periodical measurement method [117, 132, 133]
- Uniform wear method (UWM) [134]
- Offline prediction method [135, 136]
- Real time compensation method [137, 138]

A review of the key features of each method is tabulated in Table 2-4 for comparison. In principle, the reviewed tool wear compensation methods are applicable for both conventional and micro EDM. However, the real time tool wear compensation method has not been applied in micro EDM because of difficulties in counting discharge pulses due to very short pulse interval in micro EDM.

When considering the techniques to minimize the effect of corner wear, UWM offers an interesting way which was then adopted by the offline prediction method. In UWM, the tool path is designed in such a manner so that the tool can recover to its original shape. An example of the proposed tool movement in UWM is shown in Figure 2-22. Sequence (a) shows the tool path movement in X - Y plane for the first layer. Due to the occurrence of longitudinal wear, the machined surface will incline from the starting point (black circle) to the end point (white circle). To compensate this inclination, the electrode is set to follow path (b) which is the reversed direction of path (a) for the second layer. After that, the next two layers will follow path (c) and (d) consecutively. This ensures uniform wear to occur along the eroding area. The inner part and outline part are scanned alternately. When the outline part is being machined, the tool becomes rounded as a result of the corner wear. However, when the inner part is machined, discharges only occur along the bottom surface of the tool and consequently the original sharp corner is restored. In this way, the corner wear is effectively compensated.

Table 2-4. Comparison of tool wear compensation techniques

Features	Multiple Electrode Method	Periodical Measurement Method	Uniform Wear Method (UWM)	Offline Prediction Method	Real Time Compensation Method
References	[130, 131]	[117, 132, 133]	[134]	[135, 136]	[137, 138]
Application	Conventional EDM Micro EDM	Conventional EDM Micro EDM	Conventional EDM Micro EDM	Conventional EDM Micro EDM	Conventional EDM
Principle	Repeating the machining path a number of times with new or reground	Measuring the worn electrode periodically during machining process	Moving the tool along a specially designed path to ensure uniform wear occurs along the tool eroding surface wear	Moving the tool in a predictive path to compensate longitudinal	Predicting and compensating the tool wear in real time based on discharge pulse counting
Corner wear measurement & compensation	Longitudinal and corner wear are compensated by replacing the worn electrode with a new electrode which has an identical geometry	Direct measurement of the worn electrode : Electrical contact using an automatic touch sensing circuit [132] Laser sensor system [133] Machine vision system [117] Adding a compensation length after measuring the electrode wear.	Scanning the inner part and outer part of the slot alternately to restore the original shape of electrode	Adopting UWM tool path principle to restore the original shape of electrode.	Corner wear is minimized by using tubular electrode with dielectric flushing from the centre of the tool.
Longitudinal wear measurement & compensation			Adding a compensation length before each layer machining Prediction of additional compensation length: $\Delta Z = L_w \left[TWR \left(\frac{S_w}{S_e} \right) + 1 \right]$ ΔZ : depth of cut L_w : machining depth of 1 layer S_w : cross sectional area of cavity S_e : cross sectional area of the	Generating a predictive path to compensate longitudinal wear $T_p(x) = S_R(x) - C \int_0^x [S_i(x) - S_R(x)] dx$ $C = TWR \frac{p}{S_e}$ $T_p(x)$: required tool path $S_R(x)$: required surface profile $S_i(x)$: initial surface profile TWR : tool wear ratio p : machining width	Adding a compensation length in real time $ \Delta Z_{RT} $ $= \min (\Delta L_{sens} , \Delta Z_{lim})$ $\Delta L_{sens} = \frac{K_E \sum_T(t_e) N}{T_a}$ Z_{RT} : real time compensation ΔZ_{lim} : maximum compensation value ΔL_{sens} : decrease of tool length K_E : constant to determined for each machining condition $\sum(t_e)N$: sum of discharge

Table 2.5 (continued)

Features	Multiple Electrode	Periodical Measurement	Uniform Wear Method (UWM)	Offline Prediction	Real Time Compensation
Drawbacks	<ul style="list-style-type: none"> - High tool production cost - The number of electrode must be determined prior to machining - Very time consuming 	<ul style="list-style-type: none"> - Machining process must be interrupted - Time consuming - Expensive cost for developing the measurement system - Maximum nonconformance at the middle of the feature 	<ul style="list-style-type: none"> - Must predict/determine TWR value before machining - The compensation accuracy strongly depends on the accuracy of TWR input value - Maximum nonconformance at the middle of the feature occurs since the longitudinal compensation is only given at the edge of machined surface - Long machining time when machining with small layer thickness is performed in order to minimize the nonconformance at the middle of the feature 	<ul style="list-style-type: none"> - The initial surface profile must be determined before machining - Difficult to be used for workpiece with discontinuous surface - Width of cut needs to be constant during machining. - A minor error in TWR and initial surface profile input value will cause an accumulative compensation error in the machined profile. 	<ul style="list-style-type: none"> - K_E must be empirically determined for each machining condition. - The compensation accuracy depends on the accuracy of K_E input value - Difficult to be applied in micro EDM due to the very short pulse interval in micro EDM.

Figure 2-22. Tool movement in UWM [134]

Longitudinal wear compensation is the most important part which describes the quality of a tool wear compensation system. Multiple electrode method, periodical measurement method, and UWM compensate the longitudinal wear by giving an additional depth at the starting points of each new layer. This technique leads to maximum nonconformance at the middle of the machined surface due to continuous longitudinal wear while the electrode is traversing in X - Y plane. This phenomenon is presented in Figure 2-23. To avoid this issue, offline and real time prediction methods give the additional compensation lengths during the traverse of the tool in X - Y plane.

Figure 2-23 Maximum nonconformance of UWM [135]

Furthermore, when considering the calculation of the longitudinal compensation length, it is noted that UWM and offline prediction method relies on the accuracy of TWR input value which is normally taken from the handbook value. Since there is no handbook value for micro EDM, thus the reliability of these methods for compensating tool wear in micro EDM is doubtful. A marginal error in TWR input value will result in an accumulative overestimating or underestimating the tool wear, and thus resulting in inaccuracy of the machined part. Real time compensation method depends on the accuracy of K_E which is an uncontrollable parameter. Furthermore K_E must be empirically determined for each machining condition which makes this method inconvenient to be used for various machining setting. In order to avoid overestimating or underestimating the tool wear, a combined wear compensation approach is used in real time compensation method. The value of real time compensation Z_{RT} along a certain tool path segment is limited to a

maximum value ΔZ_{lim} . The real time tool wear compensation method has been experimentally proven to be able to produce accurate feature even though an unknown blank is introduced at the initial profile.

2.4 Outcome of literature review

The literature review highlighted the importance of tool wear compensation system in micro EDM to exploit its full capability in the realm of micro machining. The problems concerned and the need to carry out this research have been identified and summarized below:

- Although EDM process has been established for more than 60 years, it still lacks of a direct link between single discharge and multiple discharge material removal mechanism. EDM involves a stochastic nature which is affected by a number of various parameters. Therefore real time monitoring system is proposed as an effective method to evaluate and predict EDM process performances.
- A number of pulse discriminating systems have been reported by various researchers to evaluate the gap conditions. However all these techniques cannot be applied in micro EDM system because of the difference in pulse characteristics. There is no reliable PD system for micro EDM up till now. This research work attempts to fill this necessity.
- The geometry of tool wear in EDM involves longitudinal wear and corner wear, which need to be compensated for achieving an accurate feature. A review of the influencing factors has been done for a better understanding of the tool wear phenomenon.
- Review on existing tool wear compensation system has revealed that the real-time tool wear compensation method offers the least possibility of overestimating or underestimating the electrode wear. This method is free from complex calculation prior to machining and can be considered as the best method for tool wear compensation. However this technique is not yet available for the micro EDM. The final goal of this research will try to fulfill the necessity of real time tool wear compensation in micro EDM.

CHAPTER 3

APPROACH TO REAL TIME COMPENSATION SYSTEM FOR MICRO EDM

This chapter describes the proposed steps to develop a real time compensation system. The overview of the proposed approach is schematically presented in Figure 3-1. Four steps are necessary to construct a reliable and yet practical method to compensate and minimize the tool wear problem in micro EDM. These steps include analytical modeling, real time monitoring, estimation of erosion volume and finally the development of real time compensation system.

Figure 3-1. Schematic flowchart on the development of real time compensation system

The descriptions of the proposed steps are as follow:

1. Analytical model of micro EDM

In micro EDM, the material removal process is generated by repetitive erosion from single electrical discharges. Thus, the knowledge gathered from the generated crater geometry is directly related to the amount of material removed from the workpiece, and tool electrode.

The first step in this research work is to develop a methodology to predict the crater geometry based on the process parameter and material properties. A single discharge analytical model is developed to provide a valid prediction over a wide range of process parameter input. The adopted model is based on a well accepted electro-thermal material removal mechanism. Since several type of electro-thermal models have been developed, a brief assessment on the available models is conducted initially to select the appropriate model for anode and cathode erosion. As most of the models were developed for conventional EDM process, modification is made to ensure the appropriateness of the selected model in micro EDM process. The methodology of utilizing the model is also designed in such a way so that it can be employed in a real time prediction process. Finally, experimental work is carried out to validate the developed model. This step is described in detail at chapter 4.

2. Real time monitoring of micro EDM process

The second step of this research work is to develop a real time monitoring unit to supervise the progress of material removal during machining process. This step includes the development of discharge pulse counting and pulse discriminating module in an open architecture desktop micro EDM system.

The number of discharge pulse during machining process is counted using the discharge pulse counting module. The pulse discriminating module is developed in order to supervise any changes of the gap condition as it can effectively represent the flushing effectiveness. The combination of both modules is used to monitor the progress of material removal during machining. An experimental investigation is then carried out to validate the module as well as to study the effect of pulse distribution to the machining performance. As a real time PD module offers numerous advantages to micro EDM monitoring system, it is further used to design an adaptive speed servo

module for micro EDM. This module is able to improve the machining time of a micro EDM process. The detailed description of the real time monitoring unit can be found in chapter 5.

3. Estimation of erosion volume in micro EDM machining process

The third step of this research work is to merge the results from step 1 and step 2 into one system which can estimate the erosion volume during micro EDM machining process in real time. Modeling of material removal and tool wear volume are performed and the estimation results are analyzed by comparing them with the experimental results. An assessment on the estimation performance is then carried out to select the best parameter to be used for developing a new compensation method. The first part of chapter 6 describes this step in detail.

4. Real time compensation system for micro EDM

The outcome of step 3 is further used to develop a new compensation method for micro EDM drilling processes. Since the compensation is based on real time estimation of erosion volume, the proposed method is expected to be applicable for a wide range of energy input and machining depth setting. The capability of the proposed method to produce accurate micro hole is demonstrated experimentally by comparing it with other compensation method. This step is described at the last part of chapter 6.

The proposed steps to construct a real time compensation system are described in this chapter.

CHAPTER 4

ANALYTICAL MODEL OF MICRO EDM PROCESS

This chapter presents the analytical model of micro EDM process, which will be used to estimate the crater size from a single electrical discharge pulse. The first section describes a brief assessment on available EDM theoretical models in order to identify suitable models to be adopted in this work. The second and third sections deal with the development of electro thermal model for anode and cathode erosion respectively. The framework of this chapter is shown in Figure 4-1.

Figure 4-1. Document map of chapter 4

4.1 Brief assessment on available EDM electro thermal models

Arising from the literature review on anode-cathode erosion model, section 2.3.1 reveals that Dibitonto's model [74] assumes a point heat source for cathode erosion, provides a better agreement with experimental data as compared to other models. This conclusion is divulged after Yeo *et al.* conducted a numerical comparison of several electro thermal models and compared them with experimental results [97]. However, while point heat source will always result in a hemispherical crater shape, disk heat source is able to provide a bowl crater shape with a shallow bottom surface which is a better representative of an actual crater shape. Thus, it is concluded that disk heat source model has a potential to be further developed by incorporating a better approximation of heat flux radius and fraction of energy. This conclusion is followed up by the development of electro thermal model for anode and cathode in micro EDM using a disk heat source by Yeo *et al.* [96]. The reported model is able to provide a close approximation with experimental result with average estimation error of 2.7% and 6.6% for anode and cathode respectively.

In this work, the anode erosion model is adopted from the theoretical model developed by Yeo *et al.* [96] as it is able to provide a very good estimation result within micro EDM discharge energy regime. As for cathode erosion model, Dibitonto's [74] point heat source model is adopted due to the difficulty found in locating a single crater in the cathode material.

Tungsten rod is employed as the cathode tool electrode material in this work since it is commercially available at various sizes and has a low TWR value. As tungsten is normally made from powder metallurgy, high porosity is found on the surface of material and the size of the porosity might be bigger than the size of the crater. This causes difficulty in differentiating between a single crater and a porosity and thus measurement of single crater diameter becomes impossible. Figure 4-2 shows that the discharge crater is very indistinct with the porosity even when cemented tungsten carbide made of super fine particles (SWC) is used as the material.

Crater radius is commonly assumed as the representative of heat flux radius. Heat flux radius is normally expressed as a function of time [88, 92, 139] in which the function is frequently determined through empirical measurement of crater radius [96, 140]. Since measurement of single crater radius is unfeasible, thus it is impossible to define the heat

flux radius for tungsten material. Consequently, applying disk heat source model at cathode will not give a satisfactory result since the requirement of performing a good estimation in this model is the availability of a good approximation of heat flux radius [97].

Figure 4-2. Discharge crater in SWC material [85]

Point heat source model (PHSM) is considered as the best solution to resolve the issue of single discharge modeling in tungsten material. Since the heat source is assumed as a point, the heat source radius is not need to be defined. It is considered as the most appropriate model to provide initial approximation of EDM process [97]. Therefore the point heat source model is employed in cathode erosion modeling in this work.

4.2 Micro EDM anode erosion model

4.2.1 Anode erosion modeling based on disk heat source

The single discharge anode erosion model used in this work is adopted from the theoretical model developed by Yeo *et al.* [96] where modification is made to suit the model for a real time prediction process. Figure 4-3 shows the schematic diagram of the anode erosion model.

Figure 4-3. Schematic diagram of anode erosion model

The main simplifying assumptions used in the model are the following [96]:

- Two dimensional heat transfer
- Only one spark occurs for one discharge of energy input
- Average thermophysical properties are applied over the temperature range
- Heat transfer to electrode surface is dissipated only by conduction
- Radiation and convection heat losses are negligible
- The energy used for material removal is only contributed by the voltage and current during pulse on time
- The Gaussian heat flux is simplified by equivalent uniform heat flux
- The fraction of discharge energy going the anode and cathode is taken as constant
- The material in superheated area is removed completely while only a constant fraction of the material in the molten area is removed.

The main inputs for the model are the discharge waveform characteristics and material properties. Typical discharge voltage and current waveform in micro EDM is shown in Figure 4-4 where only the pulse on time portion of the data is used to determine the discharge energy.

Figure 4-4. Typical discharge voltage and current waveform

For each acquired discharge waveform, pulse on time (T_{on}), average voltage during pulse-on-time (V_a), and average current during pulse-on-time (I_a) are extracted. First, pulse-on-time is used to calculate the heat source radius to provide the boundary conditions for anode. The heat source radius represents the growth of plasma channel and usually expressed as a function of pulse-on-time [88]. By assuming that the heat flux diameter is close to the crater diameter, the heat flux radius for anode can be empirically determined through single discharge experiments. Based on fitting result of experimental data (as shown in Figure 4-5 and appendix A), the heat source radius is expressed as follows:

$$R_{anode} = 0.0633 \cdot T_{on}^{0.7616} \quad (4.1)$$

Where R_{anode} represents the heat flux radius at the anode in microsecond and T_{on} represents the pulse on time in nanoseconds. These parameters are then used to determine the magnitude of heat flux, q , which is assumed as a uniformly distributed heat flux with time dependent magnitude as suggested by Patel *et al.* [88]. It is expressed by the following relationship.

$$q = \frac{F_a \cdot V_a \cdot I_a}{\pi \cdot R^2} \quad (4.2)$$

Here, F_a is a combination of the fraction of energy allocated and fraction of molten area for the anode. The value of F_a is empirically determined through iteration of calculated results to fit with the experimental data. In this work, the value of F_a is found to be 14%

Figure 4-5. Crater diameter versus pulse on time (material: Ferralium)

The governing partial differential equation (PDE) for heat conduction without internal heat generation is written as

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (4.3)$$

where

$$\alpha = \frac{K_t}{\rho \cdot C_p} \quad (4.4)$$

The initial condition gives

$$T(r, z, 0) = T_0 \quad (4.5)$$

The boundary conditions are

$$-K_t \frac{\partial T}{\partial z} = \begin{cases} q, & 0 < r < R \\ 0, & r > R \end{cases} \quad (4.6)$$

$$T(\infty, \infty, t) = T_0 \quad (4.7)$$

α is the thermal diffusivity of material (m^2/s), T_0 is the ambient temperature of material (K), K_t is the material thermal conductivity (W/mK), ρ is the material density (kg/m^3) and C_p is the specific heat (J/kg.K).

Introducing dimensionless variables of $u = \frac{r}{R}$, $w = \frac{z}{R}$, $\tau = \frac{\alpha \cdot T_{on}}{R^2}$, and $\theta(u, w, \tau) = \frac{K_t \cdot T(r, z, t)}{q \cdot R}$, the solution of the abovementioned PDE can be given in a dimensionless form. The normalized temperature distribution in the vertical axis is given by [141]

$$\theta(0, w, \tau) = 2 \sqrt{\frac{\tau}{\pi}} \exp\left(-\frac{w^2}{4\tau}\right) \left[1 - \exp\left(-\frac{1}{4\tau}\right)\right] + \sqrt{w^2 + 1} \operatorname{erfc}\left(\frac{\sqrt{w^2 + 1}}{2\sqrt{\tau}}\right) - w \operatorname{erfc}\left(\frac{w}{2\sqrt{\tau}}\right) \quad (4.8)$$

Where r is the radial distance, w is the vertical distance, and erfc is the complementary error function. The normalized temperature distribution solution in the horizontal axis is given by [96]

$$\theta(u, 0, \tau) = I_1 - I_2 \quad (4.9)$$

Where the solution of the first integral, I_1 is given as follow [142]

$$I_1 = \begin{cases} \frac{2}{\pi} E(u), & 0 < u < 1 \\ \frac{2}{\pi}, & u = 1 \\ \frac{2u}{\pi} [E(u^{-1}) - (1 - u^{-2})K(u^{-1})], & u > 1 \end{cases} \quad (4.10)$$

Here, K and E are complete elliptic integrals of the first and second kind respectively. The solution of the second integral, I_2 is given by [93];

$$I_2 = \frac{1}{2\sqrt{\pi\tau}} \sum_{i=0}^{\infty} \left\{ \frac{(-1)^i i!}{(2i+1)(4\tau)^i} \sum_{j=1}^{i+1} (i-j+2) \times \left[\frac{u^{j-1}}{(j-1)!(i-j+2)} \right]^2 \right\} \quad (4.11)$$

By combining the results of equation (4.10) and (4.11) into equation (4.8), the dimensionless temperature distribution along the radial axis can be calculated.

Finally, the crater's edge temperature is determined to define the boundary where the superheated and molten material will be expelled and is expressed in dimensionless form as follows

$$\theta_{crater} = \frac{K_t(T_m - T_0)}{q \cdot R} \quad (4.12)$$

Where T_m is the material melting temperature (K)

In order to approximate the depth (h) of the crater, equation (4.8) must be solved in such a way to obtain the values of w , which makes $\theta(0, w, \tau) = \theta_{crater}$. A 2D lookup table which provides the value of θ for a certain value of τ and w was generated prior to the use of the model. Similarly, to approximate diameter (d) of the crater, equation (4.9) must be solved in such a way to obtain the values of u , which makes $\theta(u, 0, \tau) = \theta_{crater}$. Again, a 2D lookup table was generated. The table provides the value of θ for a certain value of τ and u . τ is given in the range from 0 to 5 with step size of 0.001 while w and u is given in the range from 0 to 3 with step size of 0.001.

The generated lookup tables will serve as databases to reduce the volume of calculations from a complex equation solving process into a simple 2D interpolation process. By using this method, the computational time is greatly improved and hence the model can be used in a real time prediction process.

Assuming that the micro crater has the shape of spherical cap, the volume of the crater can be calculated using the following relationship [96]:

$$V_{crater\ anode} = \frac{\pi d^2 h}{8} + \frac{\pi h^3}{6} \quad (4.13)$$

4.2.2 Anode erosion model validation

4.2.2.1 Experimental methodology

Single discharge experiment is performed in order to validate the anode erosion model. An electrical circuit is specially designed for the experimental setup where the circuit diagram is shown in Figure 4-6. The circuit consists of two main parts: RC pulse generator circuit and zero positioning circuit which are separated by switch S_8 . The RC pulse generator circuit consists of DC power supply which is set to deliver a voltage of 100 V, resistor (R), and seven capacitors (C_1 - C_7) with capacitance values vary from 1000 pF to 10000 pF. Switch 1 to 7 are used to delivered a desired discharge energy input value which can be calculated from the following relationship

$$E_{in} = \frac{1}{2} \cdot C \cdot V_{oc}^2 \quad (4.14)$$

Here, E_{in} is the discharge energy input (μ J), C is the capacitor (pF) and V_{oc} is the open circuit voltage value (V).

Figure 4-6. Circuit diagram of single discharge experiment setup

The zero positioning circuit comprises a 1.5 VDC battery source connected to the tool electrode and workpiece. The voltage and current across the workpiece-electrode gap is

measured through a voltage and current probe where the measurement results are displayed on the oscilloscope screen. The data acquisition system used in this setup includes Tektronix™ P5205 voltage probe, Tektronix™ TCP300 current probe and Tektronix™ TDS2022 oscilloscope which has a sampling frequency of 2 giga-samples per second. The motion system is constructed from three axes linear stages driven by actuators and controlled through a motion controller board (Newport™ ESP 300).

The first stage of the experiment is to detect the z-axis zero position. Switch 8 is connected to the zero positioning circuit and the tool electrode is gradually moved towards the workpiece. Once contact between tool electrode and workpiece has been established, current will flow and the tool electrode motion is stopped. The tool electrode position corresponding to the initiation of current flow is then set as zero gap distance. Next the RC pulse generator circuit is activated by toggling switch S_8 and the electrode is raised to a required gap distance of $5\mu\text{m}$. The discharge energy input is then set by selecting the required capacitor value through switch C_1 - C_7 . Finally, the RC pulse generator is triggered by pushing contact button B to release the discharge energy between the tool electrode and workpiece. The discharge voltage and current waveform are captured by the probes and recorded on the oscilloscope. The tool electrode is then moved to a new discharge location and the whole process is repeated. The detail of machining parameters used in the single discharge experiment is tabulated in Table 4-1.

Table 4-1. Machining parameters of single discharge experiment

Workpiece material	:	Stainless steel Ferralium 255 SD 50
Workpiece dimension	:	10 x 10 x 10 mm cube
Electrode material	:	Tungsten rod
Electrode diameter	:	125 μm
Dielectric fluid	:	Daphne cut HL-25 synthetic electric spark oil
Power supply voltage	:	100 V
Discharge energy input	:	5, 12.5, 20, 27.5, 35, 42.5 and 50 μJ
Polarity	:	Negative

4.2.2.2 Characterization technique

The geometry of the resulting crater from single discharge experiment is measured using Confocal PL μ imaging profiler. This equipment is used in surface metrology applications for profile and topographical measurement as well as 3D geometrical measurement of

micro scale features. It uses white light interferometry and a scanning device to create the image of the feature of interest. The resolution of this device is $0.2\ \mu\text{m}$ while the measurement ranges are $95\ \mu\text{m}$ for 20x magnification lens and $38.4\ \mu\text{m}$ for 50x and 100x magnification lenses. Lens of 100 x magnification is used to measure the crater profile in this work. Figure 4-7 shows the photograph of the measurement device while Figure 4-8 shows example of the measurement result.

Figure 4-7. Confocal PL μ imaging profiler

Figure 4-8. Profile of a typical crater captured by PL μ confocal imaging profiler

The micro craters generated from single discharge experiments are observed to have irregularities in shape. They do not have distinct outline and are not round. Therefore for each discharge energy input setting, twenty replications were made to ensure the reliability of the measurement results. Crater diameter is defined as the distance between the two peaks at the edge of crater. This definition implies that only the inner rim part of the crater is taken as the volume of a crater since the outer rim is considered to be created from material build up. For crater diameter, the measurement was done in two directions of x and y axis where the average of both values is labeled as the crater diameter. Similarly for

crater depth, measurement was done along X and Y axis where the crater depth is defined as the maximum distance from the specimen surface.

4.2.2.3 Results and discussion

The single discharge experiment is performed using discharge energy input settings shown in Table 4-1. The voltage and current waveforms were captured for each single discharge pulse from which the average voltage (V_a), average current (I_a), and pulse-on-time (T_{on}) were calculated. Together with the material properties of the workpiece material, i.e. thermal conductivity, density, specific heat, and melting temperature (shown in Table 4-2) ; these data were used to calculate the heat flux radius (R), heat flux magnitude (q), dimensionless time (τ), and crater's edge temperature (θ_{crater}). The lookup tables of crater depth and crater radius are then used to interpolate and obtain the values of dimensionless depth (w) and dimensionless radius (u) (see appendix A). These values are then used to estimate the depth (h), diameter (d) and volume ($V_{crater\ anode}$) of the micro crater. The flowchart for the calculation of crater depth, diameter and volume using the anode erosion model is shown in Figure 4-9.

Figure 4-9. Flowchart for the calculation of anode erosion model

The estimated values are then compared with the measurement results of the micro craters. The comparisons between the theoretical and experimental results are presented in Figure 4-10.

(a) Crater depth versus discharge energy input

(b) Crater diameter versus discharge energy input

(c) Crater volume versus discharge energy input

Figure 4-10. Comparison between theoretical and experimental results of anode model

Table 4-2. Thermal properties of Stainless Steel Ferralium 255

Workpiece material	:	Stainless steel Ferralium 255 SD 50
Thermal conductivity, K_T	:	14.2 W/mK
Specific heat, C_p	:	475 J/kg.K
Density, ρ	:	7880 kg/m ³
Melting temperature, T_m	:	1399 °C

Figure 4-10 shows satisfactory agreement between the estimated values and the experimental results. The statistical error of this comparison is presented in Table 4-3 where the errors are defined from the following relations

$$\text{error} = |\text{experimental value} - \text{theoretical value}| \quad (4.15)$$

$$\% \text{ error} = \frac{|\text{experimental value} - \text{theoretical value}|}{\text{experimental value}} \times 100\% \quad (4.16)$$

Table 4-3. Statistical error of the anode model validation results

	Depth		Diameter		Volume	
	(μm)	(%)	(μm)	(%)	(μm^3)	(%)
Average error	0.11	7.27	0.56	4.73	17.59	13.89
Maximum error	0.24	16.28	0.77	7.05	40.86	25.65
Minimum error	0.02	0.81	0.42	2.95	0.56	3.23
Standard deviation of error	0.09	5.58	0.12	1.40	12.97	7.67

It is observed that the best estimation is found in crater diameter where the average percentage error is only 4.7%. The average percentage errors for crater depth and volume are found to be 7.3% and 13.9% respectively. The maximum errors for the approximation of crater depth and diameter are 0.24 μm and 0.77 μm respectively while the maximum error for crater volume may achieve is 40.8 μm^3 . The discrepancies found in the results are largely attributed to the measurement process. The irregularities and non circularity at the crater surface contributed to the measurement errors.

Since the estimation error is found to be as small as 4.7%, the anode erosion model is shown to provide a reasonable estimation of the single crater size. The estimation is valid for discharge energy input of 5 μJ to 50 μJ which is prevalent in micro EDM regime.

4.3 Micro EDM cathode erosion modeling

4.3.1 Cathode erosion modeling based on point heat source

The cathode erosion model developed in this work is adopted from the theoretical model developed by Dibitonto *et al.* [74]. The model assumes one dimensional heat conduction problem for a material subjected to a point heat source on its surface. Modification is made to ensure the appropriateness of the model in micro EDM since it is adopted from conventional EDM model. In addition, modification in terms of the computational method is also performed to suit the model into real time prediction process. Figure 4-11 shows the schematic diagram of the cathode erosion model.

Figure 4-11. Schematic diagram of the cathode erosion model [74]

The model assumes a hemispherical shape of the crater where the radius of crater is equal to the depth of crater. The main assumptions of the model are the following [74, 97]:

- One dimensional heat flow with point heat source into its interior
- Plasma radius at the cathode is much smaller than the anode
- There is only one spark per pulse and the plasma radius remains small (less than $5\mu\text{m}$) allowing the use of a PHSM
- Average thermophysical properties of the cathodic material apply over the temperature range from solid to liquid melt
- The initially vaporized cavity resulting from the asymptotic temperature profile is ignored, both in terms of its contribution to the total volume eroded and to the total pulse time.
- A constant fraction of the total power is lost to the cathode, independent of current and pulse time

- Erosion takes place in molten area of an electrode
- Effects of vaporization and melting heat are neglected.

Similarly to the anode erosion model, the main inputs for the cathode model are the material properties and discharge waveform characteristics where only the pulse-on-time portion is used to determine the discharge energy.

The governing partial differential equation for one dimensional heat conduction without heat generation is written as follows

$$\frac{1}{\alpha} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \quad (4.17)$$

The initial condition is given as

$$T(r, 0) = T_0 \quad (4.18)$$

The boundary conditions of the above PDE are

$$-K_t \frac{\partial T}{\partial r} = \begin{cases} q_0, & r = 0 \\ 0, & r \neq 0 \end{cases} \quad (4.19)$$

$$T(\infty, t) = T_0 \quad (4.20)$$

In PHSM, the heat flux is defined as follow [97]

$$q = \frac{F_c \cdot V_a \cdot I_a}{2\pi \cdot r^2} \quad (4.21)$$

Here, F_c is the fraction of energy distributed the cathode. The value of F_c is empirically determined through iteration of calculated results to fit with the experimental data. In this work, the value of F_c is found to be 8.8%

The resulting temperature distribution is given by [141]

$$T(r, t) = T_0 + \left(\frac{F_c \cdot V_a \cdot I_a}{2\pi \cdot K_T \cdot r} \right) \operatorname{erfc} \left(\frac{r}{2\sqrt{\alpha \cdot t}} \right) \quad (4.22)$$

At melt radius R_m ,

$$T = T_m = T_0 + \left(\frac{F_c \cdot V_a \cdot I_a}{2\pi \cdot K_T \cdot R_m} \right) \operatorname{erfc} \left(\frac{R_m}{2\sqrt{\alpha \cdot t}} \right) \quad (4.23)$$

In order to find the crater melt radius (R_m), a dimensionless variable (β) is introduced, where β is defined as follow

$$\beta = \frac{R_m}{\sqrt{\alpha \cdot t}} \quad (4.24)$$

Then equation (4.23) can be re-arranged into

$$T_m - T_0 = \left(\frac{F_c \cdot V_a \cdot I_a}{2\pi \cdot K_T \cdot \beta \cdot \sqrt{\alpha \cdot t}} \right) \operatorname{erfc} \left(\frac{\beta}{2} \right) \quad (4.25)$$

Introducing dimensionless temperature

$$\gamma = \frac{K_T(T_m - T_0)\sqrt{\alpha \cdot t}}{F_c \cdot V_a \cdot I_a} \quad (4.26)$$

Equation (4.25) becomes

$$\gamma = \frac{\operatorname{erfc} \left(\frac{\beta}{2} \right)}{2 \cdot \pi \cdot \beta} \quad (4.27)$$

Equation (4.27) provides the dimensionless temperature distribution on the cathode material. The plot of dimensionless temperature γ versus dimensionless radius β is shown in Figure 4-12. For any instant of time, the highest dimensionless temperature always occurs at the origin and slowly decreases with increasing distance from the center where it will reach zero when dimensionless radius β reaches infinity.

Figure 4-12. Dimensionless variable γ versus β

In order to reduce the computational time, the plot in Figure 4-12 is converted into a look up table which serves as a database for the computational process. Once the value of γ has been achieved, the value of β can be determined by interpolation of the data inside PHSM look up table (see appendix B). This method will greatly reduce the computational time since the solving process of complex equation is converted into 1-D interpolation process. Thus the model can be used for real time prediction process.

Assuming that the crater shape is hemispherical, the volume of the crater can be calculated using the following relationship

$$V_{crater\ cathode} = \frac{2}{3}\pi R_m^3 \quad (4.28)$$

4.3.2 Cathode erosion model validation

4.3.2.1 Experimental methodology

Since single discharge experiment is not viable to be performed in the selected cathode material (tungsten), micro EDM milling process was conducted to validate the developed cathode erosion model. The surface roughness after machining was measured. R_a is an average roughness (hill to valley) while R_{max} is the maximum. Because so many craters overlap, R_{max} is the measurement that should correspond to the theoretical melt radius R , if all the melt were removed during the pause time [74]. This validation method is also used by Dibitonto *et al.* to validate PHSM in conventional EDM process.

An open architecture desktop micro EDM system is developed in order to perform micro EDM multiple discharge experiment. The setup will serve as the experimental platform in this research work from this point onwards. The schematic of the setup used in this work is shown in Figure 4-13 while the photograph is shown in Figure 4-14.

The experimental setup consists of a working table, a dielectric tank, a workpiece holder, an electrode holder, a DC power supply, a RC type pulse generator and a set of data acquisition and control system. The data acquisition system is used to capture the electrical parameters of each discharge pulse. All these components are assembled as shown in the schematic diagram. The tool-workpiece gap distance and the machining process can be monitored visually using CCTV camera where the display is shown in a TV monitor. The developed RC pulse generator has capacitor selection ranging from 10 pF to 4000 pF. The

detail specification of the equipment used for the data acquisition and control system are tabulated at Table 4-4.

Figure 4-13. Schematic diagram of the desktop micro EDM

Figure 4-14. Photograph of the desktop micro EDM

Table 4-4. Specification of the equipments used for data acquisition and control system

S/N	Equipment	Qty	Type	Specification
1	Motorized linear stage	1	Newport M-426 (Y axis)	25 mm travel range 325 N maximum load
		1	Newport M-462 (X-Z axis)	25 mm travel range 191 N maximum load
2	Actuators	1	Newport LTA-HS (Z axis)	50 mm travel range 0.035 μ m resolution
		2	Newport LTA-HL (X-Yaxis)	25 mm travel range 0.0074 μ m resolution
3	Motion Controller	1	Newport ESP 300	0.025 μ m resolution 10kHz communication rate
4	VoltageProbe	2	Tektronix P2220	10 x attenuation
5	Current Probe	1	Tektronix TCP 312	30 ADC
6	Current amplifier	1	Tektronix TCP A300	1 A/V – 50 A/V range DC/AC copuling
7	High Speed Digitizers	1	NI PCI-5112	100 MHz Bandwidth 100 MS/s Sampling rate
8	Multifunction DAQ card	1	NI PCI 6013	200 KS/s sampling rate 16 bit resolution
9	Oscilloscope	1	Tektronix TDS 2022	200 MHz Bandwidth 2 GS/s Sampling rate
10	Rpm regulator	1	Maxtronic	500 – 6000 rpm range

During machining, the voltage across electrode-workpiece gap is captured by the voltage probe and the signal is connected to the analog channel of the DAQ card. The signal from DAQ card is then used to monitor the average gap voltage for a traditional servo feed control strategy. The average gap voltage ($\bar{V}$) is compared with a predetermined servo reference voltage (V_s) to determine the direction of the tool electrode. When the detected average gap voltage is higher than the servo reference voltage, the electrode will be fed towards the workpiece. However when $\bar{V}$ is less than V_s , indicating the occurrence of short circuit, a feedback signal will be given to retract the electrode from the workpiece to avoid further process instability. This close loop action is given to the tool path repeatedly until the desired dimension is achieved.

To validate the cathode erosion model, micro EDM milling is conducted on tungsten material which is set as cathode. The machining is performed to fabricate slots of 600 μ m

length and 200 μm depth using a 300 μm electrode diameter. The detail machining parameters are presented in Table 4-5. For each discharge energy setting, three slots were repeated.

Table 4-5. Machining parameters of multiple discharge experiment

Workpiece material	:	Tungsten
Workpiece dimension	:	Cylinder of 10 mm diameter and 10 mm depth
Electrode material	:	Tungsten rod
Electrode diameter	:	300 μm
Machining length	:	300 μm
Machining depth	:	200 μm
Number of layer	:	6
Dielectric fluid	:	Daphne cut HL-25 synthetic electric spark oil
Power supply voltage	:	100 V
Discharge energy input	:	5, 12.5, 20, 27.5, 35, 42.5 and 50 μJ
Polarity	:	Positive

4.3.2.2 Characterization technique

Figure 4-15 (a) shows example of the surface roughness measurement results where the various color bands represent different heights on the surface thus revealing the surface topography. Figure 4-15 (b) displays the example of one surface roughness reading. For each micro slot, measurements are performed at 3 different locations as shown in Figure 4-16. For each location, a total of 6 surface roughness readings (R_{max}) were captured vertically and horizontally at predetermined lines as shown in Figure 4-15 (a). Since 3 micro slots were machined for each discharge energy setting, thus the R_{max} value for one discharge energy setting is calculated from averaging a total of 54 surface roughness measurements. This method may ensure the reliability of the measurement results.

Figure 4-15. Typical surface roughness measured by PLμ confocal imaging profiler

Figure 4-16. Location of surface roughness measurements

4.3.2.3 Results and discussion

The micro-EDM-ed surfaces at the bottom of micro slots were analyzed using SEM. The representative results are depicted in Figure 4-17 for discharge energy input of 5 μJ and 50 μJ . It can be observed that the crater size using energy input of 50 μJ is much bigger as compared to the crater size using 5 μJ energy input. Since the crater size is bigger, the surface roughness (R_a and R_{max}) is expected to be bigger at higher discharge energy input. In point heat source model, R_{max} is the measurement which is taken as the representation of theoretical melt radius (R_m) [74], assuming that all the melt are removed during the pulse-off time. The measured R_{max} value from the surface of micro slots is compared with the estimated R_m value from the developed cathode erosion model.

(a) 5 μ J discharge energy setting(b) 50 μ J discharge energy setting

Figure 4-17. SEM images of micro-EDM-ed surfaces

For each machining run, 20 voltage and current waveforms were captured from which the average voltage (V_a), average current (I_a), and pulse-on-time (T_{on}) were calculated. The average values of the collected waveform parameters are then calculated. Together with the thermal properties of the material; these data were used as the inputs to calculate the dimensionless temperature, γ . The thermal properties of tungsten are presented in Table 4-6. The PHSM look up table is then used to interpolate and obtain the dimensionless melt radius, β (see appendix B). Once the value of β has been obtained, the crater radius (R_m) and volume ($V_{crater\ cathode}$) can be determined respectively. The flowchart for the calculation of the cathode erosion model is shown in Figure 4-18.

Table 4-6. Thermal properties of tungsten

Workpiece material	:	Tungsten
Thermal conductivity, K_T	:	130.2 W/mK
Specific heat, C_p	:	141.3 J/kg.K
Density, ρ	:	19300 kg/m ³
Melting temperature, T_m	:	3387 °C

Figure 4-18. Flowchart for the calculation of cathode erosion model

Comparisons between the predicted values and experimental results are shown in Figure 4-19. It is observed that the predicted values from cathode erosion model are in a good agreement with the experimental results.

(a) Crater melt radius versus discharge energy input

(b) Crater volume versus discharge energy input

Figure 4-19. Comparison between theoretical and experimental results of cathode model

The statistical error of the model validation is presented in Table 4-7. The differences between the theoretical and experimental results are found to be comparable with the estimation error of anode erosion model. The average percentage errors are found to be 5.06% and 14.24% for crater melt radius and crater volume prediction respectively. The maximum prediction error may achieve 0.2 μm for crater melt radius and 5.34 μm^3 for crater volume. The variations between theoretical and experimental results are attributed to the measurement of data. Increasing the amount of measurement samplings may reduce the

prediction error. PHSM model assumes a hemispherical crater shape which is not the actual form of a crater. Furthermore, the assumption of R_{max} as a representation of crater melt radius is not completely true since the overlapping craters cannot represent the depth of single crater accurately. These factors may also contribute to the resulting error. The experimental results verify the validity of the cathode erosion model for single crater size estimation within discharge energy input of 5 μJ to 50 μJ .

Table 4-7. Statistical error of the cathode model validation results

	Crater melt radius		Crater Volume	
	(μm)	(%)	(μm^3)	(%)
Average error	0.08	5.06	1.41	14.24
Maximum error	0.20	9.70	5.34	25.60
Minimum error	0.03	1.85	0.22	5.35
Standard deviation of error	0.06	2.76	1.85	6.24

4.4 Summary

This chapter describes the analytical model of micro EDM process which is used to estimate the amount of material removal from a single electrical discharge pulse. A brief assessment on available EDM electro thermal models is conducted initially to select the appropriate models to be used in this research work. Based on the evaluation, disk heat source model [96] is selected for the anode erosion model while point heat source model [74] is chosen for the cathode erosion model.

Modifications were made at both models to ensure the appropriateness of applying these models into the discharge energy regime used in this work. Modification in the methodology of using the model is also made to prepare the models for a real time estimation process. Experimental works were then conducted to validate the models. The comparison results show that the analytical models are able to predict the crater size in a reasonable accuracy for discharge energy input of 5 μJ to 50 μJ . The developed analytical models will serve as a tool to predict the amount of unit removal from a single electrical spark in real time. The following chapter will provide the development of real time monitoring unit of micro EDM process.

CHAPTER 5

REAL TIME MONITORING OF MICRO EDM PROCESS

This chapter presents the development of real time monitoring unit for micro EDM process which will be used as a tool to supervise the progress of material removal during machining process. The first section of this chapter describes the development of discharge pulse counting module while the second section describes the development of pulse discriminating module for micro EDM. The third section presents the development of adaptive speed control module for micro EDM as an additional feature of the real time monitoring unit. The adaptive speed control module was developed to improve the machining time of the micro EDM process. The framework of this chapter is presented in Figure 5-1.

Figure 5-1. Document map of chapter 5

5.1 Micro EDM discharge pulse counting module

5.1.1 Development of discharge pulse counting module

Figure 5-2 shows the typical voltage and current waveforms from a RC based micro EDM system. The characteristic of RC discharge pulse is that a voltage drop is followed by a successively restoration at each discharge pulse. Hence, the number of discharge pulses can be obtained in real time by counting the falling edges of the voltage pulse. The falling edges of voltage pulse are identified when there is a negative slope across the predetermined reference voltage. The schematic diagram of discharge pulse counting process is shown in Figure 5-3.

Figure 5-2. Typical micro EDM voltage and current waveform from a RC pulse generator

Figure 5-3. Schematic diagram of discharge pulse counting process

In order to count the number of discharge pulse (N_p), a voltage probe is connected to the counter channel of the DAQ card (NI-PCI 6013). The counter channel uses simple transistor-transistor logic (TTL) algorithm with minimum input pulse width of 10 ns and maximum source frequency of 20 MHz. A program to count the falling edges of the voltage waveform is then written using a visual programming language, LabVIEWTM where the block diagram of the program is shown in Figure 5-4.

Figure 5-4. Block diagram of discharge pulse counting program

5.1.2 Module verification

A function generator (Tektronix™ AFG 3022, 25 MHz) was used to verify the reliability of the developed module. Square wave of various frequencies and amplitudes were generated using the function generator where the output signal was connected to the counter channel of the DAQ card. The developed program was tested to count the falling edges of the generated square wave. The counted number of falling edges was divided by the measurement time, and the result was then compared with the generated frequency of the square wave. A reasonable agreement has been achieved during the test. The module has been verified to be capable of counting the number of pulse with minimum pulse width of 100 ns. Accordingly, the module was verified to be used in counting micro EDM discharge pulse since the pulse-on-time used in this work is within 150 ns – 600 ns.

5.2 Micro EDM pulse discriminating module

In this work, a real time pulse discriminating (PD) module was developed in order to classify the gap pulses and to effectively detect the onset of harmful discharges. The module is aimed to provide early recognition of any process instability. Although a number

of pulse classification techniques have been described at section 2.3.2.2, none of them are applicable for micro EDM, since micro EDM has different waveform characteristics as compared to conventional EDM waveform.

5.2.1 Development of pulse discriminating module

5.2.1.1 Pulse observation and discrimination

The main difference between conventional EDM pulse and micro EDM pulse is caused by the type of pulse generator being used by each system. Conventional EDM normally uses transistor type pulse generator whilst micro EDM uses resistor-capacitor (RC) type pulse generator. The typical profile of voltage and current waveforms in conventional and micro EDM are shown in Figure 5-5. The RC type waveforms do not have a constant discharge voltage value; instead the voltage will drop until all the electrical energy stored in the capacitor has been released. Furthermore, the current pulse in micro EDM is much shorter as compared to the conventional EDM. It is apparent from the figure that similar pulse discriminating rules for a transistorized pulse generator cannot be applied to the pulse trains from a RC type pulse generator. As there is no well-established technique for classifying discharge pulse in micro EDM, a new pulse classification strategy is composed for the developed module.

Figure 5-5. Typical voltage and current waveform in (a) conventional EDM (b) micro EDM

In this work, micro EDM pulses are classified into normal discharge, delayed discharge, arcing and short circuit. The typical profiles for each type of pulses are shown in Figure 5-6.

Normal discharge is the productive discharge pulse which is the main contributor to the material removal process [98]. This pulse is randomly distributed along the eroding surface

indicating that the degree of contamination in the gap is low. Voltage drops drastically while current is flowing. For normal discharges, the voltage may drop below zero because the high discharge energy leading to the rush of massive electrons to anode instantly and cause a short-term swap of anode and cathode [113]. It is noticed from Figure 5-6 that normal discharge has the highest peak current (I_p) among the other pulses.

Figure 5-6. Typical profile of micro EDM pulses

Ideally, the RC type pulse generator should produce pulses with constant discharge duration. The discharges supposedly take place after the capacitor has been fully charged. However in practice, discharge occasionally occurs when the capacitor is not fully charged, thereby resulting in a pulse shape similar to normal discharge but with a lower peak current and lower discharge duration. This type of pulse is categorized as delayed discharge pulse as it is an analogy of a pulse with long ignition delay time in a transistorized pulse generator EDM. This type of pulse is reported to produce little material removal and results in arcs, shorts, and instability of the process [99].

Arc is considered as a harmful discharge as the voltage has not returned to open circuit voltage when the successive discharge occurs, indicating that the dielectric has not fully deionised. Arcing will cause repetitive impact of sparks on the same physical location, which damages the work-material and tool. The term 'arcing' is given since it has essentially the same destructive effect on the workpiece as a long duration arc, even though the current waveform comprises discrete pulses [100]. In micro EDM, arc discharges always come in groups of pulses with very short interval and low current amplitude value as shown in Figure 5-6.

Short circuit pulse occurs when there is a metal to metal connection between tool electrode and workpiece. Its occurrence is evident when the current is slightly raised while the voltage remains zero. Since no electrical spark occurs during the short circuit pulse, no material removal occurs.

5.2.1.2 Pulse classification strategy

The flowchart of the pulse classification strategy used in this work is shown in Figure 5-7. First, average voltage ($\bar{V}$) is used to discriminate open circuit voltage condition with discharge condition. When the average voltage is equal to open circuit voltage (V_{oc}) setting ($\pm 2\%$), no classification takes place as no discharges occur. This condition usually arises when the electrode-workpiece gap distance is too high and the applied energy is not enough to breakdown the dielectric.

Figure 5-7. Flowchart of the pulse classification strategy

When a discharged condition is observed, the number of current pulse is used to identify short circuit pulse. If no current pulse is detected, it means that the current shows a constant value, and it can be classified as short circuit. Next, the maximum voltage value (V_{max}) is used to identify arcing. When a pulse is detected with V_{max} less than open circuit voltage value ($\pm 10\%$), the pulse will be classified as arcing. Finally, peak current is introduced as a distinguishing parameter to differentiate normal discharge and delayed discharge as they have a similar form. Delay discharge is defined as a pulse with peak current lesser than 0.8 times of the maximum peak current as it lacks of sufficient charged

voltage. This criterion is empirically determined through a number of observations and is found to be fairly comparable with voltage decisive factor reported by Kwon et al. [106]. Aside from classification of discharge pulses, PD module will also calculate the percentage of each type of pulse in real time during machining.

5.2.1.3 Software of pulse discrimination

Based on the pulse classification strategy described above, a real time pulse monitoring and discriminating program was developed using a visual programming language, LabVIEW™. The discriminating strategy is based on the flowchart shown in Figure 5-7. The program was developed with a user-friendly interface as shown in Figure 5-8.

Figure 5-8. Interface of the real time pulse discriminating program

The detected voltage and current pulse are shown simultaneously at the displayed chart. The percentages of each pulse type and the machining progress bar are displayed at the bottom. Real time readings of machining time and pulse on time were also added to the interface as supporting features for monitoring system. In this program, the machining time is defined as the time difference between the first detected spark and the last detected spark during feeding sequence.

5.2.1.4 Verification of the developed pulse discriminating module

Micro EDM minimizes discharge energy which results in pulses with very short pulse duration (in sub-micro second regime); thus data acquisition system with a high sampling rate must be employed. In this module, a high speed digitizer NI PCI-5112 which has a sampling rate of 100 million samples per second is employed. The input channels of the digitizer are connected to the voltage and current probe to capture the discharge voltage and current waveforms. Each acquisition is characterized from 1000 sample points to capture the real shape of the discharge waveform.

For verifying the developed discrimination strategy, LabVIEW™ program is used to acquire and discriminate the voltage and current signals from the digitizer and subsequently display the results in spreadsheets. Figure 5-9 shows the various types of pulse captured by the developed PD module. It is confirmed that the discriminating strategy can capture and classify the discharge pulse accurately. As shown in Figure 5-9, pulses which occur when the voltage has not achieved open circuit voltage are successfully classified into arcing. Delayed discharge pulse, which has a low peak current value, is successfully differentiated from normal discharge although they have a similar shape. Furthermore the condition where voltage shows a constant zero value while current is slightly raised up from zero, is successfully identified as short circuit.

Figure 5-9. Profile of the pulses captured from the developed PD module

5.2.2 Pulse distribution study

Experiments were performed to study the distribution of each pulse type during machining using the developed pulse discriminating module. The pulse distribution is directly taken from the reading of the developed program. The effects of machining depth setting and electrode feed rate to the pulse distribution are studied. Furthermore the correlations of the pulse distribution to the machining performance such as MRR and tool wear rate are then investigated under different machining depth setting.

5.2.2.1 Experimental methodology

Micro EDM drilling and milling processes were conducted using the desktop micro EDM system. The setup of the desktop micro EDM system has been described in section 4.3.2.1. The data acquisition system uses a high speed digitizer NI-PCI 5112. Table 5-1 shows the machining parameters used in the experiments.

Table 5-1. Machining parameters in experiment of pulse distribution study

Workpiece material	: Stainless steel AISI 4140
Workpiece dimension	: 10 x 10 x 10 mm cube
Electrode material	: Tungsten rod
Electrode diameter	: 125 & 300 μm
Dielectric fluid	: Daphne cut HL-25 synthetic electric spark oil
Open Circuit Voltage	: 100 V
Discharge energy input	: 20 μJ
Electrode rotation speed	: 3000 rpm
Traversing Speed	: 10 $\mu\text{m/s}$
Feeding Speed	: 0.2 $\mu\text{m/s}$, 0.5 $\mu\text{m/s}$, 1 $\mu\text{m/s}$
Retraction Speed	: 2 $\mu\text{m/s}$
Retraction length	: 3 μm
Machining depth	: 200 μm – 900 μm

Prior to the experiments, the cube specimens were cut into two equal halves. Grinding and polishing process were conducted in order to provide a flat and smooth mating surface between the two halves. They were then wrung together and secured onto the workpiece holder table. The center of electrode was carefully positioned above the mating line prior to machining with the help of CCTV camera attached to a monitor. Machining depth, feeding speed, and retraction speed are then key-in to the developed program to start the machining process. For each experimental run, the percentage of pulse distribution and

machining time are taken at the end of experiments. These readings are provided by the developed real time pulse discriminating module. The machined profiles of electrode and workpiece are then measured to obtain the volume of material removal and tool wear.

5.2.2.2 Characterization technique

In this experiment, the characterization technique includes geometrical and dimensional measurement of tool and workpiece before and after machining. ROI OMIS II Optical Microscope is used to perform quantitative inspection of the tool and workpiece. It has 203.2 mm measurement range, 1.016×10^{-3} mm resolution, and accuracy of 4.064×10^{-3} mm. Figure 5-10 shows the photograph of this equipment while Figure 5-11 shows examples of the measurement from the equipment.

Figure 5-10. ROI OMIS II™ Optical Microscope

Figure 5-11. Geometries and profile of the hole and electrode after machining captured by ROI OMIS. The rounding corner of hole and worn electrode can be measured quantitatively by reconstructing the shape using software Autodesk Inventor Professional™. The tip point of

hole or worn electrode is taken as the reference point and minimum 6 points along the rounding outline are recorded and measured with respect to the reference point using the OMIS optical microscope. The recorded points are then used to assemble the 2D rounding outline and subsequently reconstruct the 3D geometrical features by assuming that the features of interest are axis symmetric. A feature called “iproperties” in Autodesk Inventor is used to automatically measure the volume of the constructed features. The reconstruction and volume measurement of a machined hole is depicted in Figure 5-12.

Figure 5-12. (a) Geometrical measurement of a machined hole using Optical Microscope, (b) reconstruction and volume measurement of a machined hole in the software

A similar method is also applied for measuring the electrode wear volume. The volume of worn electrode is directly reconstructed instead of reconstructing the final shape of the electrode. The total volumetric electrode wear is calculated as the summation of the volumetric longitudinal wear and volumetric corner wear as depicted in Figure 5-13. The volumetric corner wear can be obtained using “iproperties” feature from the software while the volumetric longitudinal wear can be calculated using the cylindrical volume equation as follow:

$$V_{TWL} = \frac{\pi}{4} D_{electrode}^2 (L_0 - L_i) \quad (5.1)$$

Where V_{TWL} is the volume of longitudinal tool wear (mm^3), $D_{electrode}$ is the diameter of electrode (mm), L_0 is the electrode length before machining (mm) and L_i is the electrode length after machining (mm).

Figure 5-13. Method of measuring electrode wear

The abovementioned measurement technique will be used to estimate the material removal volume and tool wear volume in this work.

5.2.2.3 Results and discussion

(a) Effect of machining depth to the pulse distribution

Machining of micro holes under various machining depth settings were conducted using tungsten electrodes of 125 μm and 300 μm diameter. The machining depth was varied from 200 μm to 800 μm while the electrode feeding speed was kept constant at 0.5 $\mu\text{m/s}$. For each given value, five observations were taken and the average pulse distribution values are presented in Figure 5-14.

Figure 5-14. Percentage of pulse distribution under various machining depth setting

Experiment results show that normal discharge was the most frequently occurring discharge pulse type for both electrode sizes. The occurrence of delayed discharge, arcing and short circuit pulses were insignificant, thus indicating that the processes were carried out in a stable condition. This stable condition may be attributed to a low feeding speed which gives more time for debris to be flushed away. As the machining depth increases, the percentage of normal discharge decreases while percentages of delayed discharge, arcing and short circuit pulses increase. This trend is correlated to the flushing effectiveness during drilling process. When drilling high aspect ratio holes, the debris removal becomes more difficult. The trapped debris inside the gap causes electric field distortion, decreasing the dielectric strength and initiates the occurrence of secondary discharges [143]. The secondary discharge occur when the capacitor is not fully charged or

more severely before the dielectric is fully deionized, consequently it will lead to the occurrence of delayed discharge and arcing respectively. A highly contaminated gap condition may also produce metal to metal connection between electrode and workpiece, and this gives rise to the occurrence of short circuit pulse.

(b) Effect of electrode feeding speed to the pulse distribution

To investigate the effect of electrode feeding speed to the pulse distribution, micro EDM drilling and micro EDM milling were conducted using tungsten electrode of 300 μm diameter under various electrode feeding speed. Micro EDM drillings were carried out to produce holes with constant depth of 900 μm while micro EDM millings were conducted to produce slots with constant length of 1000 μm and depth of 200 μm . In each setting, five observations were taken, and the average pulse distribution values are presented in Figure 5-15.

Experimental results show that as the feeding speed increases, the percentage of normal discharge decreases while the percentage of delayed discharge, arcing and short circuit increase. Again, this trend is attributed to the flushing effectiveness. As feeding speed increases, the time to flush the debris out of the gap is reduced and thus more debris is left inside the gap. The debris dispersed in the gap will increase the probability of secondary discharges such as delayed discharge, arcing and short circuit [143]. This trend is found at both micro EDM drilling and milling process. Using 0.2 $\mu\text{m/s}$ electrode feed rate, the percentage of secondary discharge is found to have 9.5% and 2.7% for micro drilling and milling respectively. When the electrode feed rate is accelerated to 1 $\mu\text{m/s}$, the percentage of secondary discharge increases significantly to 19.3% and 22.9% for micro drilling and milling respectively.

Figure 5-15. Percentage of pulse distribution under various feeding speed setting

The machining time to complete the milling process for each setting is plotted in Figure 5-16. It is observed that electrode feed rate is not proportional to the machining time. Instead, an optimum feed rate is found; which allows machining to be completed at the shortest time based on the machining condition used. At high feeding speed ($1 \mu\text{m/s}$), significant rise of short circuit and arc pulses occur. This will cause the average gap voltage to drop and initiates the control strategy to retract the electrode so as to restore to an appropriate gap condition. Excessive retracting movement at high feeding speed gives rise to the increase in machining time.

Figure 5-16. Micro EDM milling machining time versus electrode feeding speed

(c) Effect of material removal and tool wear rate on pulse distribution

In order to study the effect of material removal and tool wear rate on the pulse distribution, micro EDM drilling under various machining depth settings were conducted using an electrode of 125 μm diameter. The electrode feeding speed was kept constant at 0.5 $\mu\text{m/s}$ and the resulting machined features and tools were characterized according to the technique described in section 5.2.2.2. The machining performances being studied are material removal rate (MRR) and tool wear rate. Tool wear rate is defined as the total volume of tool wear divide by machining time. In this study, the summation of delayed discharge, arcing and short circuit pulse is labelled as secondary discharge. The experimental results are presented in Figure 5-17.

Figure 5-17. Percentage of pulse distribution versus material removal and tool wear rate

It is observed that MRR value varies throughout the machining process and it tends to decrease as the machining depth increases. At 300 μm to 800 μm machining depth setting, MRR value continuously decreases by 11.3 % while in the same regime, the percentage of normal discharge also decreases insignificantly by 9.3%. When machining depth exceeds 800 μm , excessive retraction movement occurs which will drastically reduce the MRR value by 44.2%. During retraction movement, less sparks and material removal takes place while the machining time continues to progress. Therefore, more retraction results in lesser MRR value. Interestingly, in the same regime, it is also noticed that the percentage of normal discharge drops significantly by 43.3 % following a drastic reduction of MRR value. Normal discharge can represent the variation of MRR with maximum error of 4.4% (see appendix C). Thus, it can be concluded that the percentage of normal discharge is an excellent indicator of MRR variation throughout the machining process regardless of the aspect ratio of the machined holes.

Similar with MRR, tool wear rate is also varies according to the machining depth setting. Experimental result shows that the percentage of secondary discharge can be used as an indicator of tool wear rate variation since they have a similar trend throughout the whole machining depth regime. At 300 to 800 μm machining depth regime, tool wear rate and percentage of secondary discharge increases by 55.14% and 9.11% respectively (see Appendix B). At 800 to 900 μm machining depth regime, a significant increase in tool wear rate value by 146% is followed by a drastic increase in percentage of secondary discharge by 43.3%. This similar trend occurs because there is a direct correlation between tool wear and percentage of secondary discharge. Arcing is acknowledged as the main contributor of tool wear during machining [98, 101] and arc pulse is reported to produce higher volume of material removal from tool electrode as compared to other type of pulse [105, 106]. Since delayed discharge is strongly correlated to the occurrence of arcs and shorts, and thus the higher proportion of delayed discharge, arcing and short circuit pulses detected, the higher volumetric electrode wear will occur [99].

Although a similar trend has been revealed, percentage of secondary discharge cannot represent tool wear rate variation well enough. For examples: a change in tool wear rate by 55.14% is only represented by a change in secondary discharge by 9.11% whereas a change in tool wear rate by 146% is only represented by a change in secondary discharge by 43.4%. Hence, unlike normal discharge which can be considered as an excellent

indicator of material removal rate variation, secondary discharge is not valid to be labeled as a good indicator of tool wear rate. Mechanism of tool wear during machining involves a number of other factors such as the precipitation of carbon layer, the behavior of corner wear, adherence of debris at the tool electrode, etc. The occurrence of these phenomena has been verified by various researchers as discussed in section 2.3.3.2. However, the quantitative effect of these phenomena to the tool wear mechanism has not been investigated.

5.3 Adaptive speed control module for micro EDM

Study on the pulse distribution has revealed that the machining time is not proportional to the electrode feeding speed due to the excessive occurrence of retraction movement. In order to address the issue of excessive retraction movement, the electrode feeding speed should be adjusted according to the prevailing gap condition during machining. To accomplish this, an adaptive speed control module for micro EDM will be conceptualised, in which the main input of the control strategy is the pulse distribution, taken from the developed PD module.

5.3.1 Principle of adaptive speed control module.

The percentage of pulse distribution is a direct indicator of machining stability and contains information regarding the degree of contamination inside the gap. This valuable information is used as the basic platform to build an adaptive speed servo control module. The PD module has a function to measure dynamics of the machining state, and to detect the trend towards harmful discharges.

In order to develop an adaptive speed control module, the experimental setup described in section 4.3.2.1 is modified to integrate the real time pulse discriminating module with the control strategy of micro EDM. In the new setup, the voltage and current signal are directly connected to a high speed digitizer NI PCI-5112. A new program which integrates the developed real time pulse discriminating program with the control strategy is built using LabVIEWTM software.

The discriminating gap condition for the adaptive speed servo control module was based on observation of a consistent sequence of pulse discharges, specifically, delayed discharge pulses followed by an episode of arc pulses and ending with a short circuit pulse. This

experimental observation revealed that the onset of short circuit pulse increases in probability immediately after an episode of arc pulses that follow delayed discharge pulses. Thus, detection of this sequence of pulse discharges can be used to trigger electrode retraction before further deterioration of gap condition. Previous experiment results show that the occurrence of excessive retraction movement is the source of longer machining time. The retraction movement takes place when the gap is highly contaminated causing instability in the process. However, applying slower electrode feeding speed can help to restore the machining stability as indicated by reduction of secondary discharge in Figure 5-15.

These findings are adopted as the basis of the adaptive speed servo control module. The adaptive control module adjusts and finds the optimum feed rate value which varies throughout the machining process. The detailed principle of the adaptive speed servo control module is described in flowchart as shown in Figure 5-18.

Figure 5-18. Flowchart of adaptive speed control module

The main components of the developed adaptive speed control module are the pulse discriminating module which is used to analyze the pulse distribution. Gap voltage and current signal captured during the process are discriminated by the developed PD module.

Each type of pulse is counted and the distribution of each pulse is analyzed. Results of pulse distribution analysis perform two main functions: determining the direction of electrode movement (feeding or retracting) and adjusting the feed rate of the electrode. Retraction of electrode from the workpiece takes place when either one of the following conditions occurs:

- Short circuit pulse is detected
- Arc pulses are detected after delayed discharge pulses

The pulse type distribution is used to determine the feed rate gain which reduces the feed rate input value. The higher the percentage of arc pulses, delayed discharge pulses, or short circuit pulses, the higher feed rate gain will be given and this reduces the feeding speed further. The determination of feed rate gain is given by the following linear equation.

$$G_t = C(\%DD + \%Arc + \%SC) \quad (5.2)$$

Where G_t is the feed rate gain at a particular machining time, t ; C is a predetermined constant, and $\%DD$, $\%Arc$, $\%SC$ is the percentage of delayed discharge, arcing, and short circuit pulse at a particular machining time, t , respectively.

The controlled movement of electrode ensures the EDM process happens in an appropriate condition without excessive retraction movement. The voltage and current signal from the gap are then returned to the pulse discriminating module to provide a close loop system for the servo control strategy.

5.3.2 Adaptive speed control module performance

Figure 5-19 plots the machining time versus machining depth for drilling micro holes of 900 μm depth. The initial feeding speeds used are 0.5 $\mu\text{m/s}$ and 1 $\mu\text{m/s}$. The experiments were conducted using electrode diameter of 300 μm with other machining conditions described in Table 5-1.

(a) initial feeding speed of 0.5 μm/s

(b) initial feeding speed of 1 μm/s

Figure 5-19. Performance of adaptive speed control module

For initial feeding speed of 0.5 μm/s, the developed module was able to improve the machining time by 32 minutes or 54.95 % while for initial feeding speed of 1 μm/s the improvement was 38 minutes or 57.5% with respect to the machining time of a common EDM servo system. The operating procedure of the common servo system has been described in section 2.2.2.2. This improvement is attributed to the implemented PD module and adaptive speed feature. The adaptive speed feature automatically slows down the electrode feeding speed as the machining state deteriorates. When a higher percentage of delayed discharge, arcing, or short circuit is detected, the higher feed rate gain (G_f) will be produced as shown in equation (5.2). G_f will reduce the feeding speed as shown in the block diagram (Figure 5-18). Slower electrode feeding speed allows more time for gap flushing and reduces the number of retracting movement which prolongs the overall machining time. PD module differentiates discharge pulses and gives a particular corrective action for each acquisition; thereby improving the speed and sensitivity of servo reaction to the machining state. Figure 5-19 also shows that during the early stages of machining process, the adaptive speed servo module did not adjust the machining speed significantly. However as machining depth increases, the effects of adaptive speed control module were progressively observed. For initial feeding speed 0.5 μm/s, the adaptive speed servo modules starts to give a noticeable improvement at 500 μm machining depth, while for initial feeding speed of 1 μm/s, the improvement is already noticed at 300 μm machining depth. At initial feeding speed setting of 1 μm/s, harmful machining state occurs

earlier as compared to that of $0.5 \mu\text{m/s}$ feeding speed; therefore the adaptive speed servo module will give earlier modification to the electrode feeding speed. It can be concluded that the adaptive speed servo module performs a better improvement of machining time for higher initial feeding speed setting. The typical machined features from the experiments are shown in Figure 5-20.

Figure 5-20. Resulting machined features of adaptive speed control module

The depth of the resulting features is found to be considerably far from the programmed depth of $900 \mu\text{m}$. This difference is attributed to the electrode wear. However, it can be observed that the adaptive speed control module produce more accurate depth as compared to that of a common servo feed system. The depth error is reduced to 2.9% for initial feeding speed of $0.5 \mu\text{m/s}$ and 4% for initial feeding speed of $1 \mu\text{m/s}$. Another advantage of using the adaptive speed servo system is a smaller amount of electrode wear since the occurrence of arc discharges, which is the main contributor of tool wear [98, 101, 105], is reduced. As shown in Figure 5-15, machining with slower feeding speed results in less arcing, and hence reduce the occurrence of arcs and minimize the electrode wear.

5.4 Summary

This chapter describes the development of real time monitoring unit for micro EDM process. The proposed unit consists of two main parts; discharge pulse counting module and pulse discriminating module. The development and verification of both modules have been described comprehensively at the first two sections of this chapter.

The developed pulse discriminating module was then used to study the pulse type distribution during machining and the following findings are revealed:

- The pulse distribution can be used as an indicator to represent the flushing effectiveness as well as the degree of contamination inside the discharge gap
- Percentage of normal discharge is an excellent real time indicator of MRR variation throughout the machining process. It represents the variation of MRR with maximum error of 4.4%.
- Percentage of secondary discharge (delayed discharge, arcing, and short circuit) has a similar trend with tool wear rate variation during machining. However, secondary discharge cannot be considered as a reliable indicator of tool wear rate. A change of tool wear rate by 55.14% is only represented by a change of secondary discharge by 9.11% whereas a change of tool wear rate by 146% is only represented by a change of secondary discharge by 43.4%.
- Machining time is not proportional to the electrode feeding speed due to the occurrence of retraction of electrode. An optimum feeding speed, which allows machining to be completed at the shortest time, exists for each particular machining setting.
- Experimental observation revealed that the onset of short circuit pulse increases in probability immediately after an episode of arc pulses that follow discharge delay pulses.

Based on the findings observed in the pulse distribution study, the developed real time pulse discriminating module was used to construct an adaptive speed control module as an additional feature of the real time monitoring unit. The following results are achieved using the developed module:

- For initial feeding speed of 0.5 $\mu\text{m/s}$ the developed adaptive speed control module was able to improve the machining time up to 54.95% and reduce the machining depth error to 2.9%.
- For initial feeding speed of 1 $\mu\text{m/s}$ the developed adaptive speed control module was able to improve the machining time up to 57.5% and reduce the machining depth error to 4%.

The following chapter will provide the last two steps in this research work which are about the real time estimation of erosion volume and development of real time compensation system for micro EDM.

CHAPTER 6

REAL TIME COMPENSATION SYSTEM FOR MICRO EDM

This chapter presents the development of a real time compensation system for micro EDM. There are two components developed in this chapter: erosion volume model and real time compensation system. The first three sections of this chapter describe the development of erosion volume model including material removal volume model and tool wear volume model. The proposed models combine the analytical single discharge model described in chapter 4 and real time monitoring unit described in chapter 5. The models are then integrated into micro EDM system to estimate the erosion volume of machining process in real time. The estimation results of material removal and tool wear volume are then analyzed. The last section of this chapter describes the development of a real time compensation system for micro EDM. The performance of the proposed system is tested and validated through experimental comparisons with other methods. The framework of this chapter is shown in Figure 6-1.

Figure 6-1. Document map of chapter 6

6.1 Erosion volume model

It is understood that the volume of eroded material from workpiece and tool electrode is proportional to the sum of elementary craters volume created by individual electric discharges. Accordingly, a combination of single crater size prediction and real time discharge pulse counting module can be used to predict the material removal and tool wear volume during machining process in real time. The aforementioned logic is the basis of the proposed erosion model.

6.1.1 Material removal volume model

The total volume of material removed from a workpiece by EDM process can be approximated by the following relationship

$$V_{MR} = \bar{V}_{crater\ anode} \cdot N_p \cdot \%ND \cdot C_{MR} \quad (6.1)$$

where V_{MR} is the total volume of material removed from the workpiece, $\bar{V}_{crater\ anode}$ is the average volume of single crater per discharge pulse at anode material, N_p is the number of discharge pulse, $\%ND$ is the percentage of normal discharge pulse and C_{MR} is an empirical factor to account the effect of overlapping craters. Percentage of normal discharge ($\%ND$) is introduced into the calculation to take into account the effects of undesirable discharges such as delayed discharge, arcing and short circuit. Furthermore, $\%ND$ has been found as a good real time indicator of MRR variation during micro EDM drilling process (see section 5.2.2.3).

Material removal factor, C_{MR} , is introduced considering that the total volume of two discrete craters is bigger than the total volume of two overlapping craters. This condition is illustrated in Figure 6-2 where the volume of craters in condition 1 (no craters overlapped) is bigger than the volume of craters in conditions 2 and 3 (craters are overlapped). The amount of craters overlapping influences the total volume of material removal. This effect is illustrated in Figure 6-2 where the volume of craters in condition 2 is bigger than the volume of craters in condition 3. C_{MR} also represents the amount of craters overlapping at the workpiece. In this work, factor C_{MR} is expressed as a function of number of discharge pulse, N_p .

Figure 6-2. Illustration of overlapping craters

Experimental work is performed to obtain the relation between numbers of discharge pulse and C_{MR} . Micro EDM drilling was conducted to produce micro holes of 600 μm depth using various discharge energy setting. The actual volume of micro holes ($V_{MR \text{ actual}}$) was determined by measuring the cross section profile of the machined holes as described in section 5.2.2.2. Voltage and current across the discharge gap were captured in real time and they are used to determine the N_p , $\bar{V}_{crater}$, and $\%ND$ values. N_p is obtained using the discharge pulse counting module described in section 5.1. The pulse discriminating module, described in section 5.2, is used to obtain $\%ND$. $\bar{V}_{crater \text{ anode}}$ is obtained by averaging the values of crater volume from each detected discharge waveform. The crater volume is estimated using the anode erosion model described in section 4.2.1.

Following the relation found in equation (6.1), the material removal factor, C_{MR} can be calculated as follows

$$C_{MR} = \frac{V_{MR \text{ actual}}}{\bar{V}_{Crater \text{ anode}} \cdot N_p \cdot \%ND} \quad (6.2)$$

The relationship between material removal factor and number of discharge pulse is presented in Figure 6-3. It is observed that C_{MR} decreases gradually as N_p increases before it reaches a steady value. This trend is attributed to the distribution of electric field intensity at workpiece surface as explained by Ivanov *et al.* [119]. In early stage of machining process, the electric field intensity is uniformly distributed at the workpiece surface (see Figure 2-18a) and consequently the amount of craters overlapping is low. When machining achieves a certain depth (180 μm), a high electric field intensity region is created at the center of the hole and it forms a uniform shape (see Figure 2-18e). Consequently, the amount of craters overlapping increases in this area until a steady value is achieved. The steady value shows that a uniform shape of electric field intensity has been formed. This trend agrees with the behavior of overlapping craters at the workpiece

observed in the experiment. A power regression curve fitting is then performed to define the relationship as presented in equation (6.3)..

$$C_{MR} = 43.596 \cdot N_p^{-0.369} \quad (6.3)$$

Figure 6-3. Approximate relationship between C_{MR} and N_p

6.1.2 Tool wear volume model

Similar to the material removal model, the tool wear volume can be approximated by the following relationship.

$$V_{TW} = \bar{V}_{crater\ cathode} \cdot N_p \cdot (1 + \%SD) \cdot C_{TW} \quad (6.4)$$

$$\%SD = \%DD + \%Arc + \%SC \quad (6.5)$$

where V_{TW} is the total volume of material removed from the tool electrode, $\bar{V}_{crater\ cathode}$ is the average volume of single crater per discharge pulse at cathode material (tool electrode), N_p is the number of discharge pulse, $\%SD$ is the percentage of secondary discharge pulse and C_{TW} is an empirical factor labeled as tool wear factor. Percentage of secondary discharge, $\%SD$ is added into the calculation to take into account the effects of undesirable discharge. It is defined as the summation of delayed discharge, arcing and short circuit pulses as shown in equation (6.5). These secondary discharges are reported to contribute a higher amount of erosion volume at tool electrode as compared to normal discharge pulse [101, 105]. The occurrence of secondary discharge will increase the tool

wear volume and its effect is defined as $(1+\%SD)$ in this work. This expression follows the expression used in uniform wear method where $(1+TWR)$ is used to represent an increase in tool wear volume. Furthermore, $\%SD$ has been observed to have a similar trend with tool wear rate variation during micro EDM drilling process (see section 5.2.2.3), thus it can reduce the error which comes from secondary discharges.

The tool wear factor is introduced to account the effect of overlapping craters. It represents the amount of craters overlapping. Similar with C_{MR} factor, C_{TW} factor is expressed as a function of number of discharge pulse, N_p . C_{TW} can be determined as follows:

$$C_{TW} = \frac{V_{TW \text{ actual}}}{\bar{V}_{Crater \text{ cathode}} \cdot N_p \cdot (1 + \%SD)} \quad (6.6)$$

The relationship between tool wear factor and number of discharge pulse is depicted in Figure 6-4. It is observed that C_{TW} increases gradually as N_p increases until it reaches a steady value. This trend is attributed to the distribution of electric field intensity at electrode surface as explained by Ivanov *et al.* [119]. In the early stage of machining, the highest electric field intensity region is concentrated at the edge of the electrode (see Figure 2-18a), consequently the amount of craters overlapping becomes very high at the edge of the tool. When machining achieves a certain depth, the highest electric field intensity region is dispersed at the centre part of the electrode and forms a uniform shape (see Figure 2-18e). As a result, the amount of craters overlapping will also decrease until a steady value is achieved. The steady value shows that the electric field intensity has formed a uniform shape. This trend agrees with the behavior of overlapping craters at the tool observed in the experiment. A power regression curve fitting is then performed to define the relationship as presented in equation (6.7).

$$C_{TW} = 0.0118 \cdot N_p^{0.2151} \quad (6.7)$$

Figure 6-4. Approximate relationship between C_{TW} and N_p

6.2 Development of real time erosion volume estimation system

The discharge pulse counting module, pulse discriminating module, along with anode and cathode erosion model are combined to build a real time system for erosion volume estimation in micro EDM. The discharge pulse counting module, pulse discriminating module, and anode and cathode erosion models are assembled in one setup to predict the material removal and tool wear volume using the model proposed in section 6.1.1 and 6.1.2. The schematic diagram of the proposed system is shown in Figure 6-5.

In the proposed system, the gap voltage and current waveform from micro EDM process are acquired and sent to a real time monitoring and control PC which will return a feedback control signal to the motion controller. The data acquisition system uses a data acquisition card (NI-PCI 6013) and a digitizer card (NI-PCI 5112). The data acquisition card NI-PCI 6013 has several input channels. First, the analog input channel is used to monitor average gap voltage and performs traditional servo feed control system. Second, the counter channel is used to count the number of discharge pulse. The digitizer NI-PCI 5112 is connected to both voltage and current probe to acquire the discharge voltage and current in real time. The acquired waveforms are then used to discriminate micro EDM pulses and predict the crater size at anode and cathode.

Figure 6-5. Schematic diagram of the real time erosion volume estimation system

The interface of the real time estimation program is shown in Figure 6-6. The program provides the values of $V_{crater\ anode}$, $V_{crater\ cathode}$, N_p , %ND, and %SD. These values are then used as the inputs for material removal and tool wear volume models. The thermal properties of the anode and cathode material as well as machining settings are required to be specified for the program to perform machining process and to predict the erosion volume. The profile of voltage and current waveforms are displayed only at the pulse-on-time portion. The interface also shows the machining progress bar, number of discharge pulse, average crater size, percentage distribution of pulses, and the estimated erosion volume in real time.

Figure 6-6. Interface of the developed real time estimator of erosion volume for micro EDM

6.3 System verification and performance analysis

Experiments were performed to study the performance of the developed system in predicting of material removal and tool wear volume under various machining depth settings and discharge energy inputs. The details of experimental parameters are shown in Table 6-1. Two observations were taken for each experimental run (see appendix D).

Table 6-1. Experimental parameters for estimation of erosion volume

Workpiece material	:	Stainless steel Ferralium 255 SD 50 Titanium alloy (Ti – 6Al – 4V) Nickel alloy A400 UNS4400
Workpiece dimension	:	10 x 10 x 10 mm cube
Electrode material	:	Tungsten rod
Electrode diameter	:	125 μm
Dielectric fluid	:	Daphne cut HL-25 synthetic electric spark oil
Open Circuit Voltage	:	100 V
Discharge energy input	:	5, 20, 35, 50 μJ
Electrode rotation speed	:	3000 rpm
Feeding Speed	:	0.5 $\mu\text{m/s}$,
Machining depth	:	300, 600, 900 μm

6.3.1 Material removal volume verification

The comparison of the estimated material removal volume with the experimental results is presented in Figure 6-7. In this work, the term ‘estimation error’ is used to represent the difference between the actual value with the estimated value according the following relation:

$$\text{Estimation error} = \frac{|\text{actual value} - \text{estimated value}|}{\text{actual value}} \times 100\% \quad (6.8)$$

It is observed that the estimation of material removal volume has a satisfactory agreement with the experimental results with overall average error of 13.18%. The average estimation errors using discharge energy input of 5, 20, 35, and 50 μJ are equal to 16.6%, 14.1%, 8.2%, and 13.8% respectively. The method can be applied at various machining depth settings and discharge energy inputs since there is no trend observed between the estimation error with energy input or machining depth setting. Thus the differences between the estimated and actual values are largely due to error in measuring of

experimental data. The rounding corners and concavity at the wall side of the holes may contribute to inaccuracy in measurement of actual holes diameter and actual material removal volume. The imprecision of single crater size estimation from the electro-thermal model may also contribute to the errors. Improving the accuracy of theoretical single crater model may improve the overall accuracy of material removal volume estimation.

Figure 6-7. Comparison of material removal for stainless steel

Under the proposed method, the estimation error is found unrelated with the machining depth setting as shown in Figure 6-7. This happens because the proposed method has considered the effect of undesirable discharges which frequently occurs at higher machining depth. This condition also implies the merit of using pulse discrimination module for estimating the volume of material removal in real time. A previous work by Jung *et al.* [144] has attempted to use the number of discharge pulses to estimate the material removal volume in micro EDM process. It is reported that the relationship between material removal volume with the number of discharge pulse is only proportional at drilling low aspect ratio micro holes. For aspect ratio higher than 3, large values of standard deviation are found which shows that material removal volume is no longer proportional to the number of discharge pulse due to the occurrence of abnormal discharges [144]. Consequently, large value of estimation error is produced at high aspect ratio micro holes. By introducing the percentage of normal discharge pulse (%ND) in addition to the number of discharge pulses, a good estimation can be performed regardless of the aspect ratio of the holes being machined. The percentage of normal discharge can

help resolve with the error which comes from undesirable discharges in drilling high aspect ratio holes. The experimental results show that the system can perform a good estimation of material removal volume under various machining depth settings and energy inputs.

Further experimental work using titanium and nickel alloy workpiece material is performed. The thermal properties of the workpieces are presented in Table 6-2. The comparisons of the estimated material removal volume with the experimental results are depicted in Figure 6-8 and Figure 6-9. A good agreement with the experimental result is achieved with average error of 10.6% for titanium and 8.9% for nickel alloy material. These results imply that by applying an appropriate C_{MR} factor, the system is able to perform a good approximation of material removal volume for various machining depth settings, energy inputs or material properties.

Figure 6-8. Comparison of material removal for titanium

Figure 6-9. Comparison of material removal for nickel alloy

Table 6-2. Thermal properties of Titanium and Nickel Alloy

Materials	Titanium (Ti-6Al-4V)	Nickel Alloy A400 UNS 4400
Thermal conductivity, K_t	21.9 W/mK	21.8W/mK
Specific heat, C_p	523.5 J/kg.K	427 J/kg.K
Density, ρ	4506 kg/m ³	8800 kg/m ³
Melting temperature, T_m	1941 °C	1325 °C

6.3.2 Tool wear volume verification

The comparison of the estimated tool wear volume with the experimental result for machining ferralium 255 material is depicted in Figure 6-10. It is observed that the estimation of tool wear volume shows a relatively good agreement with the experimental results with overall average error of 17.5%.

The estimation error is found to be independent of the energy input setting. The estimation errors using discharge energy input of 5, 20, 35, and 50 μJ are 21%, 17.3%, 12.9%, and 18.8% respectively. Poor estimation results were observed during drilling hole of 900 μm depth in which the maximum estimation error can reach 35.49%.

Figure 6-10. Comparison between estimated tool wear volume estimation with experimental data

The discrepancy found between the estimated tool wear volume and the experimental data can be attributed to the following factors:

- (a) The quantitative effect of secondary discharge

Secondary discharge such as arcing is acknowledged as the main contributor of tool wear during machining [98, 101]. It is reported to produce higher amount of material removal from tool electrode as compared to normal pulse [105, 106]. Therefore, it is essential to understand the contribution of secondary discharge to the tool wear volume quantitatively. The introduction of %SD has effectively represented the occurrence rate of secondary discharge. However, the contribution of secondary discharge to the amount of erosion volume has not been considered qualitatively in the proposed method. This may explain the high estimation error found in drilling 900 μm hole depth. Under this setting, secondary discharge occurs frequently with an average percentage value of 31% (see appendix D).

(b) Adherence of debris at the side of the tool.

Yu *et al.* reported that when a hole is drilled to a certain depth, the debris ejected from the working area begins to attach and accumulate on the surface of electrode. This condition initiates discharges to occur at the inner side of the hole [145]. Since these discharges occur between the debris and the inner side of the hole, there will be no material eroded from the tool electrode. This phenomenon implies that there are certain discharges which are not contributing to the tool wear and thus they will mislead the prediction of tool wear volume. The adherence of debris at the side of the tool is illustrated in Figure 6-11.

Figure 6-11. Adherence of debris at the side of the tool [145]

(c) Precipitation of carbon layer on electrode surface

The phenomenon of adhering carbon layer to the electrode surface during EDM process is observed by Mohri *et al.* [115, 121]. The attached carbon layer has an effect of protecting the electrode from wear erosion. It is reported that tool wear ratio decreases with the increase of the carbon composition at the layer [123]. The influence of carbon layer to the resulting tool wear is not negligible as it may alter the tool wear ratio value up to 3.5% as shown in Figure 2-21. Since this phenomenon is not considered in the proposed method, it may contribute to the estimation error found in the experiment.

(d) Inaccuracy of single crater size prediction

Another factor which may contribute to the discrepancy of the data pertains to the error prediction of single crater size. The single discharge cathode erosion model used in this work has an average estimation error of 14.24%. This error may affect the performance of the system in predicting the erosion volume during machining process. Furthermore, the electro thermal model assumes a certain profile of crater but in actual case, the crater shape is not uniform.

(e) Measurement error

The attached debris creates a concave shape of the tool and this may influence the accuracy of tool wear measurement. This factor also contributes to the resulting estimation error.

Tool wear mechanism is more complicated as compared to material removal mechanism at workpiece. It involves a number of factors which affect the behavior of tool wear. Therefore, it is more difficult to perform accurate prediction on tool wear volume as compared to material removal volume.

6.3.3 Comparative analysis

The development of a compensation system requires a reliable estimation of the material removal volume or tool wear volume to determine the required compensation infeed. Performance analysis of both predictions is performed to compare and select the best parameter to be utilized for developing a compensation system. The statistical error of material removal and tool wear volume prediction for ferralium 255 workpiece material is presented in Table 6-3 and Table 6-4.

Table 6-3. Estimation error of erosion volume prediction

Depth setting (μm)	Percentage estimation error (%)							
	5 μJ		20 μJ		35 μJ		50 μJ	
	MR	TW	MR	TW	MR	TW	MR	TW
300	31.30	19.99	22.46	20.89	10.02	17.16	5.98	10.98
600	6.95	7.54	15.85	22.81	6.09	7.44	18.18	30.53
900	11.56	35.49	4.02	8.26	8.35	14.18	17.39	14.93

Table 6-4. Statistical error of erosion volume prediction

	Total	
	MR	TW
Average percentage error	13.18	17.52
Maximum percentage error	31.30	35.49
Minimum percentage error	4.02	7.44
Standard deviation error	8.12	8.97

It is observed that the proposed method performs a better prediction on material removal volume as compared to that of the tool wear volume. This condition is found at all levels of discharge energy input and machining depth setting. The average estimation error for material removal prediction is 13.18% while the average error for tool wear prediction achieves 17.52%. The estimated value of tool wear volume may differ as high as 35.49% from the actual value.

Although similar prediction approaches are undertaken, the proposed method performs a better prediction of material removal volume due to the following reasons:

- Material removal volume is estimated using disk heat source model, which gives a better representation of the actual crater size as compared to point heat source model used in prediction of tool wear volume.
- %ND indicates the variation of material removal with higher accuracy as compared to %SD which indicates the variation of tool wear volume (discussed in section 5.2.2.3).
- Adherence of debris and precipitation of carbon layer on tool electrode contributes to the error in estimating the tool wear volume. This phenomenon does not occur at the workpiece; hence a better prediction on material removal volume can be performed.

The following section describes the development of real time compensation system based on material removal volume estimation.

6.4 Development of real time compensation system for micro EDM

Existing tool wear compensation methods, such as uniform wear method (UWM), is based on a predetermined tool wear ratio (TWR) value [134, 135, 137]. In this work, a new compensation system is developed in which a predicted value of material removal volume is employed. The main objective of every tool wear compensation method is to fabricate accurate micro features, thus the usage of material removal volume value is considered to be better than TWR value since it is a direct illustration of the resulting feature of interest.

6.4.1 Principle of real time compensation system

In this work, a new micro EDM drilling scheme is proposed, in which the material removal volume is estimated as an indication of the machining progress. The flowchart of the proposed method is shown in Figure 6-12.

The targeted material removal volume, V_{target} , can be calculated using a cylindrical volume equation as follow

$$V_{target} = \frac{\pi}{4} \cdot D_{hole}^2 \cdot Z \quad (6.9)$$

Where

$$D_{hole} = D_{electrode} + (2 \times g) \quad (6.10)$$

Here, Z is the machining depth setting (mm), D_{hole} is the approximated hole diameter (mm), $D_{electrode}$ is the diameter of the electrode (mm) and g is the maximum discharge gap (mm). In this method, it is assumed that the discharge gap at the peripheral of the tool is equal to the gap at the end of tool.

Subsequently, the additional compensation length (Δh) can be determined using the following expression:

$$\Delta h = \frac{4(V_{target} - V_{MR})}{\pi D_{hole}^2} \quad (6.11)$$

Where V_{MR} is the estimated material removal volume from equation (6.1).

Figure 6-12. Flowchart of the proposed compensation method

In this proposed method, the developed erosion volume estimator (described in section 6.2) is used to continuously predict the ongoing material removal volume, V_{MR} in real time. The captured discharge waveforms are used to estimate the crater size (V_{crater}), percentage of normal discharge (%ND) and number of discharge pulse (N_p). These values are then used to estimate the material removal volume in real time using equation (6.1). Given a certain input value of machining depth setting (Z) and electrode diameter ($D_{electrode}$), the targeted material removal volume (V_{target}) can be calculated using equation (6.9). The targeted material removal volume is then compared with the predicted real time value of material removal volume. The difference between both values ($V_{target} - V_{MR}$) is then used to determine the additional compensation length (Δh) using equation (6.11). The calculated compensation length (Δh) is then added to the machining depth setting (Z) and the summation result is sent as a feedback signal to the Z-axis linear stage. Consequently, the servo feed control system will command the electrode to drill until a depth of $\Delta h + Z$ is reached. This process is repeatedly performed until the estimated material removal volume equals to the targeted material removal volume ($V_{target} = V_{MR}$), in which, the machining process is terminated. This new micro EDM drilling scheme is applied on the desktop micro EDM system.

6.4.2 Real time compensation system performance

Experimental work is conducted in order to demonstrate the quality of the proposed method. The proposed method is compared with the normal machining method and the uniform wear method. Normal machining method is defined as a drilling process without tool wear compensation. Uniform wear method is an offline tool wear compensation method, developed by Yu *et al.* [134], and has been adopted by many authors [124, 135, 146]. In this method, the tool wear is predicted prior to machining using the following relation:

$$\Delta Z = L_w \cdot \left(1 + TWR \frac{S_w}{S_e}\right) \quad (6.12)$$

Here, ΔZ is the compensation depth, L_w is the machined depth, S_w is the cross sectional area of the cavity (X-Y plane), and S_e is the cross sectional area of the electrode (X-Y plane). TWR is empirically determined prior to machining process. For drilling process, S_w is assumed to be equal to S_e and hence equation (6.12) becomes:

$$\Delta Z = L_w \cdot (1 + TWR) \quad (6.13)$$

The comparison is performed using machining parameters as shown in Table 6-5.

Table 6-5. Machining parameters for compensation system verification

Workpiece material	: Stainless steel Ferralium 255 SD 50
Workpiece dimension	: (10 x 10 x 10) mm ³
Electrode material	: Tungsten rod
Electrode diameter	: 125 μ m
Dielectric fluid	: Daphne cut HL-25 synthetic oil
Open Circuit Voltage	: 100 V
Discharge energy input	: 35 μ J
Electrode rotation speed	: 3000 rpm
Feeding Speed	: 0.5 μ m/s
Machining depth	: 300, 600, 900 μ m

Figure 6-13 shows the comparative assessments of the existing methods with the proposed method while the resulting machined micro features are shown in Figure 6-14. It is observed that the proposed method is able to produce more accurate hole depth as compared to the other methods. In comparison with normal machining method, the

proposed system is able to improve the depth error by 3.23%, 5.65 %, and 12.1% for depth settings of 300, 600, and 900 μm respectively. The proposed system is also observed to perform better compensation as compared to the uniform wear method since it reduced the depth error of UWM by 7.14%, 0.86%, and 2.07% for depth settings of 300, 600, and 900 μm respectively. Statistical t-test was performed and result shows that the proposed method produces smaller error as compared to UWM with confidence level of 99%. Result of the statistical t-test is shown in Appendix E.

Figure 6-13. Comparative analysis between normal machining, UWM, and the proposed method

The experimental results also show that the proposed method is more reliable than UWM. The variation of the resulting machined depth in the proposed method is much smaller as compared to UWM especially at 600 μm and 900 μm depth. The average variation of depth error in UWM is 6.7% while the average variation of depth error in the proposed method is only 3.4% (see Appendix E). Furthermore, it is also observed that the proposed method tends to underestimate the target depth, while UWM may either underestimate or overestimate the target value.

	Normal method		Uniform wear method		Proposed method	
300 μm depth setting
	machined depth	depth error	machined depth	depth error	machined depth	depth error
	283.88 μm	5.37 %	327.84 μm	9.28 %	294.37 μm	2.14 %
600 μm depth setting
	machined depth	depth error	machined depth	depth error	machined depth	depth error
	542.5 μm	9.58 %	612.88 μm	4.79 %	576.42 μm	3.93 %
900 μm depth setting
	machined depth	depth error	machined depth	depth error	machined depth	depth error
	755.23 μm	16.09 %	868.81 μm	6.06 %	864.1 μm	3.99 %

Figure 6-14. Comparison between the proposed method with normal machining and uniform wear method

The improvement made is attributed to the real time approach used by the proposed system. Unlike UWM which utilizes an offline compensation approach, the proposed method monitors the progress of material removal volume in real time through the developed real time monitoring unit (described in chapter 5). Hence the proposed method performs a better monitoring approach, including the occurrence of undesirable discharges, and thus more accurate control of the process can be achieved. Furthermore, the proposed method employs material removal volume which is directly related to the resulting feature of interest whereas UWM utilizes a predetermined TWR value which is an indirect parameter.

The plausible reasons for the depth error using the proposed method are attributed to the following factors:

(a) Concavity of the hole

Equation (6.9) assumes a constant hole diameter to calculate the targeted material removal volume (V_{target}). However, experimental results show that hole diameter enlarges as the machining depth increases. The average hole diameter for machining depth settings of 300, 600 and 900 μm are 146.4 μm , 158.2 μm , and 164.4 μm respectively. The increase in hole diameter is caused by the concavity produced at the wall side of the hole. This phenomenon happens due to the difficulties in flushing of debris out of the gap, especially at deeper holes. Some of the trapped debris inside the gap are localized and create debris-rich regions at the side gap which initiate secondary discharges at the side of the tool. Simulation on debris movement inside the gap, using a computational fluid dynamics (CFD) program, shows that at deeper depth, the more localized debris-rich regions are created between the center and lower part of the side gap [147]. Consequently, more discharges will occur at the side gap and bigger concavity of the side hole is created when drilling deeper holes. This concavity leads to a larger hole diameter being produced. Giving the same hole diameter for all depth settings will make the calculated V_{target} value smaller than the required actual material removal volume. Thus the estimated compensation length will tend to underestimate at deeper machining depth setting.

(b) Corner erosion effect

In this method, the targeted material removal volume is determined through a cylindrical volume equation which assumes a cylindrical shape of the hole. Due to the corner erosion, the actual hole will have a rounding corner and thus this assumption will contribute to the error in determining the compensation length needed (Δh). The proposed method has not considered the corner erosion phenomenon.

Despite the abovementioned drawbacks, the proposed method is able to improve the machining accuracy significantly. The proposed method is able to reduce the depth error to 3.35% only; while UWM and normal machining methods result in a depth error of 6.7% and 10.4% respectively.

6.5 Summary

The implementation of micro EDM analytical model and real time monitoring unit to predict micro EDM machining performance has been described in this chapter. The developed models and modules are assembled into one setup to estimate the erosion volume of micro EDM machining process in real time. Experimental work with the developed system has been performed to validate the performance of the system. Experimental result has revealed that the proposed system yields better estimation of material removal as compared to tool wear volume. Therefore, the material removal volume is selected as a suitable parameter for developing a new compensation system.

A new compensation system is then developed, in which the real time estimation of material removal volume is used as the monitoring parameter. The proposed system is able to improve the machining accuracy significantly as compared to normal machining method and uniform wear method. The following chapter will provide the conclusions of this research work and the recommendations for the future work.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This chapter presents the overall conclusion of the research work done. Recommendations for future work are also described.

7.1 Conclusions

The occurrence of tool wear in micro EDM has become the major setback of the process. A method to compensate tool wear is needed to exploit the full capability of micro EDM in producing accurate micro features. In this research work, a system which combines a theoretical electro-thermal model and real time monitoring process has been developed in order to estimate the erosion volume of a micro EDM process in real time. The developed system is then used to design a new micro EDM compensation method.

The following conclusions are drawn from the work done:

1. Analytical models have been adopted to approximate the amount of material removal from a single electrical discharge pulse at anode and cathode in micro EDM. Based on the available models evaluation, disk heat source model is selected for the anode erosion model while point heat source model is adopted for the cathode erosion model. The overall trend has shown that the models are able to provide a satisfactory approximation of crater geometry on the anode and cathode material. The model is able to predict the crater geometry with average error of 4.73% for crater diameter, 7.27% for crater depth, and 13.89% for crater volume in the case of anode. As for the cathode, the average percentage errors are found to be 5.06% for the crater melt radius and 14.24% for the crater volume.
2. A real time monitoring unit for micro EDM process has been developed in order to supervise the stochastic material removal mechanism during machining. The unit consists of discharge pulse counting module and pulse discriminating module. The pulse type distribution has been shown as a good indicator of flushing effectiveness as well as the degree of contamination inside the discharge gap. A study on pulse distribution has proposed the percentage of normal discharge pulse as a reliable

indicator of material removal variation during machining. Although a similar trend has been revealed, percentage of secondary discharge pulse cannot be considered as a reliable indicator of tool wear rate since their variation is in a different magnitude.

3. As an additional feature of the real time monitoring unit, an adaptive speed control module for micro EDM process has been developed using the pulse discriminating module as its basic platform. The developed module is able to improve the machining time up to 57.5% and reduce the depth error up to 4%.
4. A real time system to estimate the material removal and tool wear volume has been developed. The developed system combines the analytical models and the real time monitoring unit. Experimental verification showed that the developed system is able to perform a good estimation of material removal volume at various energy settings, machining depth settings, and material properties. The average error of material removal estimation is 13.18% for stainless steel, 10.9% for titanium and 8.9% for nickel alloy material. For the case of tool wear, the average estimation error achieves 17.5% for machining stainless steel material. Comparative analysis shows that the system performs better estimation on material removal volume as compared to that of the tool wear volume.
5. A new compensation system was developed based on the real time material removal estimation. The required compensation length is calculated and adjustment is given repeatedly until the targeted material removal volume is reached. Experimental work shows that the proposed system is more accurate and reliable as compared to the uniform wear method. At 900 μm machining depth setting, the proposed method is able to reduce the dimensional error to 4% only, while the uniform wear method reduce the dimensional error to 6%.

7.2 Future work

Future work in the following areas is recommended:

1. Improvement of micro EDM analytical model

The approach taken in single discharge model development implies that the reliability of the analytical model is highly dependent on the accuracy of empirical heat flux radius and fraction of energy approximation. Improvement on the empirical approximation of heat flux radius and fraction of energy for wider energy input and various material properties will enhance the accuracy of the analytical model.

2. Quantitative assessment on the effect of secondary discharges to the erosion volume

The developed pulse discriminating module has successfully illustrated the occurrence rate of secondary discharge which deteriorates machining stability. Investigations on the contribution of secondary discharge to the amount of tool wear volume can improve the accuracy of tool wear estimation since secondary discharge is known as the main contributor of tool wear.

3. Investigation on the characteristics of corner erosion

The corner erosion at the workpiece and tool has affected the accuracy of compensation length prediction. An investigation on the characteristic of corner erosion at a wide range of energy input and material properties may improve the accuracy of the compensation system.

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APPENDIX A ANODE EROSION MODEL RESULTS

(a) Crater depth look up table

τ/w	0.000	0.060	0.120	0.180	0.240	0.300	0.360	0.420	0.480	0.540	0.600	0.660	0.720	0.780	0.840	0.900	0.960	1.020	1.080	1.140	1.200	1.260	1.320	1.380	1.440	1.500
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.040	0.226	0.171	0.126	0.090	0.062	0.042	0.027	0.017	0.010	0.006	0.003	0.002	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.080	0.318	0.261	0.212	0.170	0.134	0.104	0.079	0.060	0.044	0.032	0.023	0.016	0.011	0.008	0.005	0.003	0.002	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000
0.120	0.383	0.326	0.275	0.230	0.191	0.156	0.127	0.102	0.081	0.064	0.049	0.038	0.029	0.022	0.016	0.012	0.009	0.006	0.004	0.003	0.002	0.001	0.001	0.001	0.000	0.000
0.160	0.434	0.377	0.325	0.278	0.236	0.199	0.167	0.138	0.114	0.093	0.076	0.061	0.049	0.039	0.030	0.024	0.018	0.014	0.011	0.008	0.006	0.004	0.003	0.002	0.002	0.001
0.200	0.474	0.416	0.364	0.316	0.273	0.234	0.200	0.170	0.143	0.120	0.100	0.083	0.068	0.056	0.045	0.036	0.029	0.023	0.018	0.014	0.011	0.009	0.007	0.005	0.004	0.003
0.240	0.507	0.449	0.396	0.348	0.304	0.264	0.228	0.196	0.168	0.143	0.122	0.103	0.086	0.072	0.060	0.049	0.041	0.033	0.027	0.022	0.018	0.014	0.011	0.009	0.007	0.005
0.280	0.534	0.476	0.423	0.374	0.329	0.289	0.252	0.220	0.190	0.164	0.141	0.121	0.103	0.087	0.074	0.062	0.052	0.043	0.036	0.030	0.024	0.020	0.016	0.013	0.011	0.009
0.320	0.557	0.500	0.446	0.397	0.352	0.311	0.273	0.240	0.209	0.182	0.158	0.137	0.118	0.101	0.087	0.074	0.063	0.053	0.045	0.038	0.031	0.026	0.022	0.018	0.015	0.012
0.360	0.578	0.520	0.466	0.416	0.371	0.329	0.292	0.257	0.226	0.199	0.174	0.152	0.132	0.114	0.099	0.085	0.073	0.062	0.053	0.045	0.038	0.033	0.027	0.023	0.019	0.016
0.400	0.595	0.537	0.484	0.434	0.388	0.346	0.308	0.273	0.242	0.213	0.188	0.165	0.144	0.126	0.110	0.095	0.083	0.071	0.062	0.053	0.045	0.039	0.033	0.028	0.024	0.020
0.440	0.611	0.553	0.499	0.449	0.403	0.361	0.322	0.287	0.255	0.226	0.200	0.177	0.156	0.137	0.120	0.105	0.092	0.080	0.069	0.060	0.052	0.045	0.039	0.033	0.028	0.024
0.480	0.625	0.567	0.513	0.463	0.417	0.374	0.335	0.300	0.268	0.238	0.212	0.188	0.166	0.147	0.130	0.114	0.100	0.088	0.077	0.067	0.058	0.051	0.044	0.038	0.033	0.028
0.520	0.637	0.579	0.525	0.475	0.429	0.386	0.347	0.311	0.279	0.249	0.222	0.198	0.176	0.156	0.138	0.122	0.108	0.095	0.084	0.074	0.064	0.056	0.049	0.043	0.037	0.032
0.560	0.649	0.591	0.537	0.486	0.440	0.397	0.358	0.322	0.289	0.259	0.232	0.207	0.185	0.165	0.147	0.130	0.115	0.102	0.090	0.080	0.070	0.062	0.054	0.048	0.042	0.036
0.600	0.659	0.601	0.547	0.497	0.450	0.407	0.368	0.332	0.298	0.268	0.241	0.216	0.193	0.173	0.154	0.138	0.122	0.109	0.097	0.086	0.076	0.067	0.059	0.052	0.046	0.040
0.640	0.669	0.611	0.556	0.506	0.459	0.416	0.377	0.340	0.307	0.277	0.249	0.224	0.201	0.180	0.161	0.144	0.129	0.115	0.103	0.091	0.081	0.072	0.064	0.057	0.050	0.044
0.680	0.677	0.619	0.565	0.515	0.468	0.425	0.385	0.349	0.315	0.285	0.257	0.231	0.208	0.187	0.168	0.151	0.135	0.121	0.108	0.097	0.086	0.077	0.068	0.061	0.054	0.048
0.720	0.686	0.627	0.573	0.523	0.476	0.433	0.393	0.356	0.323	0.292	0.264	0.238	0.215	0.194	0.174	0.157	0.141	0.127	0.114	0.102	0.091	0.081	0.073	0.065	0.058	0.051
0.760	0.693	0.635	0.581	0.530	0.483	0.440	0.400	0.363	0.330	0.299	0.270	0.245	0.221	0.200	0.180	0.163	0.147	0.132	0.119	0.107	0.096	0.086	0.077	0.069	0.062	0.055
0.800	0.700	0.642	0.588	0.537	0.490	0.447	0.407	0.370	0.336	0.305	0.277	0.251	0.227	0.206	0.186	0.168	0.152	0.137	0.123	0.111	0.100	0.090	0.081	0.073	0.065	0.058
0.840	0.707	0.649	0.594	0.544	0.497	0.453	0.413	0.376	0.342	0.311	0.283	0.257	0.233	0.211	0.191	0.173	0.157	0.142	0.128	0.116	0.104	0.094	0.085	0.076	0.069	0.062
0.880	0.713	0.655	0.600	0.550	0.503	0.459	0.419	0.382	0.348	0.317	0.288	0.262	0.238	0.216	0.196	0.178	0.161	0.146	0.132	0.120	0.108	0.098	0.088	0.080	0.072	0.065

Appendix A

$\tau \backslash w$	0.000	0.060	0.120	0.180	0.240	0.300	0.360	0.420	0.480	0.540	0.600	0.660	0.720	0.780	0.840	0.900	0.960	1.020	1.080	1.140	1.200	1.260	1.320	1.380	1.440	1.500
0.920	0.719	0.660	0.606	0.555	0.508	0.465	0.425	0.387	0.353	0.322	0.293	0.267	0.243	0.221	0.201	0.183	0.166	0.151	0.137	0.124	0.112	0.102	0.092	0.083	0.075	0.068
0.960	0.724	0.666	0.611	0.561	0.514	0.470	0.430	0.393	0.358	0.327	0.298	0.272	0.248	0.226	0.205	0.187	0.170	0.155	0.141	0.128	0.116	0.105	0.095	0.087	0.078	0.071
1.000	0.729	0.671	0.617	0.566	0.519	0.475	0.435	0.398	0.363	0.332	0.303	0.276	0.252	0.230	0.210	0.191	0.174	0.159	0.144	0.131	0.120	0.109	0.099	0.090	0.081	0.074
1.040	0.734	0.676	0.621	0.571	0.524	0.480	0.439	0.402	0.368	0.336	0.307	0.281	0.257	0.234	0.214	0.195	0.178	0.162	0.148	0.135	0.123	0.112	0.102	0.093	0.084	0.077
1.080	0.739	0.680	0.626	0.575	0.528	0.484	0.444	0.407	0.372	0.341	0.312	0.285	0.261	0.238	0.218	0.199	0.182	0.166	0.152	0.138	0.126	0.115	0.105	0.096	0.087	0.079
1.120	0.743	0.685	0.630	0.580	0.532	0.489	0.448	0.411	0.376	0.345	0.316	0.289	0.264	0.242	0.221	0.203	0.185	0.169	0.155	0.142	0.129	0.118	0.108	0.098	0.090	0.082
1.160	0.747	0.689	0.635	0.584	0.537	0.493	0.452	0.415	0.380	0.349	0.320	0.293	0.268	0.246	0.225	0.206	0.189	0.173	0.158	0.145	0.132	0.121	0.111	0.101	0.093	0.084
1.200	0.751	0.693	0.638	0.588	0.540	0.497	0.456	0.419	0.384	0.352	0.323	0.296	0.272	0.249	0.228	0.209	0.192	0.176	0.161	0.148	0.135	0.124	0.113	0.104	0.095	0.087
1.240	0.755	0.697	0.642	0.591	0.544	0.500	0.460	0.422	0.388	0.356	0.327	0.300	0.275	0.252	0.232	0.213	0.195	0.179	0.164	0.151	0.138	0.127	0.116	0.106	0.098	0.089
1.280	0.758	0.700	0.646	0.595	0.548	0.504	0.463	0.426	0.391	0.359	0.330	0.303	0.278	0.256	0.235	0.216	0.198	0.182	0.167	0.153	0.141	0.129	0.119	0.109	0.100	0.092
1.320	0.762	0.704	0.649	0.598	0.551	0.507	0.467	0.429	0.395	0.363	0.333	0.306	0.282	0.259	0.238	0.219	0.201	0.185	0.170	0.156	0.143	0.132	0.121	0.111	0.102	0.094
1.360	0.765	0.707	0.653	0.602	0.554	0.511	0.470	0.432	0.398	0.366	0.336	0.309	0.285	0.262	0.241	0.222	0.204	0.187	0.173	0.159	0.146	0.134	0.124	0.114	0.105	0.096
1.400	0.768	0.710	0.656	0.605	0.558	0.514	0.473	0.435	0.401	0.369	0.339	0.312	0.287	0.265	0.244	0.224	0.206	0.190	0.175	0.161	0.148	0.137	0.126	0.116	0.107	0.098
1.440	0.771	0.713	0.659	0.608	0.561	0.517	0.476	0.438	0.404	0.372	0.342	0.315	0.290	0.267	0.246	0.227	0.209	0.193	0.178	0.164	0.151	0.139	0.128	0.118	0.109	0.100
1.480	0.774	0.716	0.662	0.611	0.564	0.520	0.479	0.441	0.406	0.374	0.345	0.318	0.293	0.270	0.249	0.229	0.212	0.195	0.180	0.166	0.153	0.141	0.130	0.120	0.111	0.102
1.520	0.777	0.719	0.665	0.614	0.566	0.522	0.482	0.444	0.409	0.377	0.348	0.321	0.296	0.273	0.251	0.232	0.214	0.198	0.182	0.168	0.155	0.143	0.132	0.122	0.113	0.104
1.560	0.780	0.722	0.667	0.616	0.569	0.525	0.484	0.447	0.412	0.380	0.350	0.323	0.298	0.275	0.254	0.234	0.216	0.200	0.185	0.171	0.158	0.146	0.134	0.124	0.115	0.106
1.600	0.783	0.724	0.670	0.619	0.572	0.528	0.487	0.449	0.414	0.382	0.353	0.326	0.300	0.277	0.256	0.237	0.219	0.202	0.187	0.173	0.160	0.148	0.136	0.126	0.117	0.108
1.640	0.785	0.727	0.672	0.622	0.574	0.530	0.489	0.452	0.417	0.385	0.355	0.328	0.303	0.280	0.258	0.239	0.221	0.204	0.189	0.175	0.162	0.150	0.138	0.128	0.119	0.110
1.680	0.788	0.729	0.675	0.624	0.577	0.533	0.492	0.454	0.419	0.387	0.357	0.330	0.305	0.282	0.261	0.241	0.223	0.206	0.191	0.177	0.164	0.152	0.140	0.130	0.120	0.111
1.720	0.790	0.732	0.677	0.626	0.579	0.535	0.494	0.456	0.421	0.389	0.360	0.332	0.307	0.284	0.263	0.243	0.225	0.208	0.193	0.179	0.166	0.153	0.142	0.132	0.122	0.113
1.760	0.792	0.734	0.680	0.629	0.581	0.537	0.496	0.459	0.424	0.392	0.362	0.335	0.309	0.286	0.265	0.245	0.227	0.210	0.195	0.181	0.167	0.155	0.144	0.133	0.124	0.115
1.800	0.794	0.736	0.682	0.631	0.583	0.539	0.499	0.461	0.426	0.394	0.364	0.337	0.311	0.288	0.267	0.247	0.229	0.212	0.197	0.182	0.169	0.157	0.146	0.135	0.125	0.116
1.840	0.797	0.738	0.684	0.633	0.586	0.541	0.501	0.463	0.428	0.396	0.366	0.339	0.313	0.290	0.269	0.249	0.231	0.214	0.199	0.184	0.171	0.159	0.147	0.137	0.127	0.118
1.880	0.799	0.741	0.686	0.635	0.588	0.544	0.503	0.465	0.430	0.398	0.368	0.341	0.315	0.292	0.271	0.251	0.233	0.216	0.200	0.186	0.173	0.160	0.149	0.138	0.129	0.120
1.920	0.801	0.743	0.688	0.637	0.590	0.546	0.505	0.467	0.432	0.400	0.370	0.343	0.317	0.294	0.273	0.253	0.235	0.218	0.202	0.188	0.174	0.162	0.151	0.140	0.130	0.121
1.960	0.803	0.745	0.690	0.639	0.592	0.547	0.507	0.469	0.434	0.402	0.372	0.344	0.319	0.296	0.274	0.255	0.236	0.219	0.204	0.189	0.176	0.164	0.152	0.142	0.132	0.123
2.000	0.805	0.746	0.692	0.641	0.593	0.549	0.508	0.471	0.436	0.403	0.374	0.346	0.321	0.298	0.276	0.256	0.238	0.221	0.205	0.191	0.178	0.165	0.154	0.143	0.133	0.124

(b) Crater diameter lookup table

τu	0.000	0.060	0.120	0.180	0.240	0.300	0.360	0.420	0.480	0.540	0.600	0.660	0.720	0.780	0.840	0.900	0.960	1.020	1.080	1.140	1.200	1.260	1.320	1.380	1.440	1.500
0.000	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞	∞
0.040	0.226	0.226	0.226	0.226	0.226	0.225	0.225	0.225	0.224	0.223	0.220	0.217	0.212	0.204	0.192	0.156	0.307	9.823	-2E2	3.6E+3	6.2E4	9.7E5	1.4E7	1.9E8	2.5E9	3E+10
0.080	0.318	0.317	0.317	0.317	0.316	0.315	0.313	0.311	0.308	0.304	0.298	0.290	0.281	0.267	0.250	0.225	0.189	0.121	0.080	0.056	0.039	0.027	0.019	0.013	0.009	0.006
0.120	0.383	0.383	0.383	0.381	0.380	0.377	0.374	0.370	0.365	0.358	0.350	0.339	0.326	0.310	0.289	0.261	0.221	0.149	0.105	0.077	0.057	0.043	0.032	0.024	0.018	0.013
0.160	0.434	0.434	0.432	0.431	0.428	0.425	0.420	0.415	0.408	0.400	0.389	0.377	0.361	0.342	0.319	0.288	0.246	0.172	0.126	0.095	0.073	0.057	0.044	0.034	0.026	0.020
0.200	0.474	0.473	0.472	0.470	0.467	0.463	0.457	0.451	0.442	0.433	0.421	0.407	0.390	0.369	0.343	0.311	0.267	0.191	0.143	0.111	0.088	0.069	0.055	0.044	0.035	0.028
0.240	0.507	0.506	0.505	0.502	0.498	0.494	0.487	0.480	0.471	0.460	0.447	0.432	0.413	0.391	0.364	0.331	0.286	0.208	0.158	0.125	0.100	0.081	0.066	0.053	0.043	0.035
0.280	0.534	0.533	0.532	0.529	0.525	0.520	0.513	0.505	0.495	0.483	0.469	0.453	0.433	0.410	0.382	0.348	0.302	0.223	0.172	0.138	0.112	0.091	0.075	0.062	0.051	0.042
0.320	0.557	0.557	0.555	0.552	0.548	0.542	0.535	0.526	0.515	0.503	0.488	0.471	0.451	0.427	0.398	0.363	0.316	0.236	0.184	0.149	0.122	0.101	0.084	0.070	0.058	0.048
0.360	0.578	0.577	0.575	0.572	0.567	0.561	0.554	0.544	0.533	0.520	0.505	0.487	0.467	0.442	0.412	0.376	0.328	0.248	0.196	0.160	0.132	0.110	0.092	0.077	0.065	0.055
0.400	0.595	0.595	0.593	0.589	0.584	0.578	0.570	0.561	0.549	0.536	0.520	0.502	0.480	0.455	0.425	0.388	0.340	0.259	0.206	0.169	0.141	0.118	0.100	0.085	0.072	0.06
0.440	0.611	0.610	0.608	0.605	0.600	0.593	0.585	0.575	0.563	0.550	0.534	0.515	0.493	0.467	0.437	0.399	0.350	0.269	0.215	0.178	0.149	0.126	0.107	0.091	0.078	0.067
0.480	0.625	0.624	0.622	0.618	0.613	0.607	0.598	0.588	0.576	0.562	0.546	0.526	0.504	0.478	0.447	0.409	0.360	0.278	0.224	0.186	0.157	0.133	0.114	0.098	0.084	0.073
0.520	0.637	0.637	0.634	0.631	0.626	0.619	0.610	0.600	0.588	0.573	0.557	0.537	0.514	0.488	0.457	0.418	0.369	0.286	0.232	0.194	0.164	0.140	0.120	0.104	0.089	0.077
0.560	0.649	0.648	0.646	0.642	0.637	0.630	0.621	0.611	0.598	0.584	0.567	0.547	0.524	0.497	0.465	0.427	0.377	0.294	0.239	0.201	0.171	0.147	0.126	0.109	0.095	0.083
0.600	0.659	0.658	0.656	0.652	0.647	0.640	0.631	0.620	0.608	0.593	0.576	0.556	0.533	0.506	0.474	0.435	0.384	0.301	0.246	0.207	0.177	0.153	0.132	0.115	0.100	0.087
0.640	0.669	0.668	0.666	0.662	0.656	0.649	0.640	0.629	0.617	0.602	0.584	0.564	0.541	0.513	0.481	0.442	0.391	0.308	0.253	0.214	0.183	0.158	0.137	0.120	0.105	0.092
0.680	0.677	0.677	0.674	0.670	0.665	0.658	0.649	0.638	0.625	0.610	0.592	0.572	0.548	0.521	0.488	0.449	0.398	0.314	0.259	0.220	0.189	0.164	0.143	0.125	0.109	0.096
0.720	0.686	0.685	0.682	0.678	0.673	0.665	0.656	0.645	0.632	0.617	0.599	0.579	0.555	0.527	0.495	0.455	0.404	0.320	0.264	0.225	0.194	0.169	0.147	0.129	0.114	0.100
0.760	0.693	0.692	0.690	0.686	0.680	0.673	0.664	0.652	0.639	0.624	0.606	0.585	0.561	0.534	0.501	0.461	0.410	0.326	0.270	0.230	0.199	0.173	0.152	0.134	0.118	0.104
0.800	0.700	0.699	0.697	0.693	0.687	0.680	0.670	0.659	0.646	0.630	0.612	0.592	0.568	0.540	0.507	0.467	0.415	0.331	0.275	0.235	0.204	0.178	0.156	0.138	0.122	0.108
0.840	0.707	0.706	0.703	0.699	0.694	0.686	0.677	0.665	0.652	0.636	0.618	0.597	0.573	0.545	0.512	0.472	0.420	0.336	0.280	0.240	0.208	0.182	0.160	0.142	0.126	0.111
0.880	0.713	0.712	0.709	0.705	0.700	0.692	0.683	0.671	0.658	0.642	0.624	0.603	0.579	0.550	0.517	0.477	0.425	0.341	0.284	0.244	0.213	0.186	0.164	0.146	0.129	0.115
0.920	0.719	0.718	0.715	0.711	0.705	0.698	0.688	0.677	0.663	0.648	0.629	0.608	0.584	0.555	0.522	0.482	0.430	0.345	0.289	0.248	0.217	0.190	0.168	0.149	0.133	0.118
0.960	0.724	0.723	0.721	0.717	0.711	0.703	0.693	0.682	0.668	0.653	0.634	0.613	0.589	0.560	0.527	0.486	0.434	0.350	0.293	0.252	0.221	0.194	0.172	0.153	0.136	0.121
1.000	0.729	0.728	0.726	0.722	0.716	0.708	0.698	0.687	0.673	0.657	0.639	0.618	0.593	0.565	0.531	0.491	0.438	0.354	0.297	0.256	0.224	0.198	0.175	0.156	0.139	0.125

Appendix A

$\tau \backslash u$	0.000	0.060	0.120	0.180	0.240	0.300	0.360	0.420	0.480	0.540	0.600	0.660	0.720	0.780	0.840	0.900	0.960	1.020	1.080	1.140	1.200	1.260	1.320	1.380	1.440	1.500
1.040	0.734	0.733	0.731	0.726	0.720	0.713	0.703	0.692	0.678	0.662	0.643	0.622	0.598	0.569	0.535	0.495	0.442	0.358	0.301	0.260	0.228	0.201	0.179	0.159	0.142	0.128
1.080	0.739	0.738	0.735	0.731	0.725	0.717	0.708	0.696	0.682	0.666	0.648	0.626	0.602	0.573	0.539	0.499	0.446	0.361	0.304	0.264	0.231	0.204	0.182	0.162	0.145	0.130
1.120	0.743	0.742	0.740	0.735	0.729	0.722	0.712	0.700	0.687	0.670	0.652	0.630	0.606	0.577	0.543	0.502	0.450	0.365	0.308	0.267	0.234	0.208	0.185	0.165	0.148	0.133
1.160	0.747	0.746	0.744	0.739	0.733	0.726	0.716	0.704	0.691	0.674	0.656	0.634	0.609	0.581	0.547	0.506	0.453	0.368	0.311	0.270	0.238	0.211	0.188	0.168	0.151	0.136
1.200	0.751	0.750	0.748	0.743	0.737	0.730	0.720	0.708	0.694	0.678	0.659	0.638	0.613	0.584	0.550	0.509	0.457	0.372	0.314	0.273	0.241	0.214	0.191	0.171	0.154	0.138
1.240	0.755	0.754	0.751	0.747	0.741	0.733	0.724	0.712	0.698	0.682	0.663	0.641	0.616	0.587	0.553	0.512	0.460	0.375	0.317	0.276	0.244	0.216	0.193	0.174	0.156	0.141
1.280	0.758	0.758	0.755	0.751	0.745	0.737	0.727	0.715	0.701	0.685	0.666	0.645	0.620	0.591	0.557	0.516	0.463	0.378	0.320	0.279	0.246	0.219	0.196	0.176	0.159	0.143
1.320	0.762	0.761	0.759	0.754	0.748	0.740	0.730	0.719	0.705	0.688	0.670	0.648	0.623	0.594	0.560	0.519	0.466	0.381	0.323	0.282	0.249	0.222	0.199	0.179	0.161	0.146
1.360	0.765	0.764	0.762	0.758	0.751	0.744	0.734	0.722	0.708	0.692	0.673	0.651	0.626	0.597	0.563	0.522	0.469	0.383	0.326	0.284	0.252	0.224	0.201	0.181	0.163	0.148
1.400	0.768	0.768	0.765	0.761	0.755	0.747	0.737	0.725	0.711	0.695	0.676	0.654	0.629	0.600	0.565	0.524	0.471	0.386	0.328	0.287	0.254	0.227	0.203	0.183	0.166	0.150
1.440	0.771	0.771	0.768	0.764	0.758	0.750	0.740	0.728	0.714	0.698	0.679	0.657	0.632	0.602	0.568	0.527	0.474	0.389	0.331	0.290	0.257	0.229	0.206	0.186	0.168	0.152
1.480	0.774	0.774	0.771	0.767	0.761	0.753	0.743	0.731	0.717	0.700	0.681	0.660	0.634	0.605	0.571	0.530	0.477	0.391	0.333	0.292	0.259	0.231	0.208	0.188	0.170	0.154
1.520	0.777	0.776	0.774	0.769	0.763	0.755	0.745	0.734	0.719	0.703	0.684	0.662	0.637	0.608	0.573	0.532	0.479	0.394	0.336	0.294	0.261	0.234	0.210	0.190	0.172	0.156
1.560	0.780	0.779	0.777	0.772	0.766	0.758	0.748	0.736	0.722	0.706	0.687	0.665	0.639	0.610	0.576	0.534	0.481	0.396	0.338	0.296	0.263	0.236	0.212	0.192	0.174	0.158
1.600	0.783	0.782	0.779	0.775	0.769	0.761	0.751	0.739	0.725	0.708	0.689	0.667	0.642	0.613	0.578	0.537	0.484	0.398	0.340	0.299	0.265	0.238	0.214	0.194	0.176	0.160
1.640	0.785	0.784	0.782	0.777	0.771	0.763	0.753	0.741	0.727	0.711	0.692	0.670	0.644	0.615	0.580	0.539	0.486	0.400	0.342	0.301	0.268	0.240	0.216	0.196	0.178	0.162
1.680	0.788	0.787	0.784	0.780	0.774	0.766	0.756	0.744	0.729	0.713	0.694	0.672	0.647	0.617	0.583	0.541	0.488	0.402	0.344	0.303	0.270	0.242	0.218	0.198	0.180	0.164
1.720	0.790	0.789	0.786	0.782	0.776	0.768	0.758	0.746	0.732	0.715	0.696	0.674	0.649	0.619	0.585	0.543	0.490	0.404	0.346	0.305	0.271	0.244	0.220	0.200	0.182	0.166
1.760	0.792	0.791	0.789	0.784	0.778	0.770	0.760	0.748	0.734	0.717	0.698	0.676	0.651	0.621	0.587	0.545	0.492	0.406	0.348	0.307	0.273	0.246	0.222	0.201	0.183	0.167
1.800	0.794	0.794	0.791	0.787	0.780	0.772	0.762	0.750	0.736	0.720	0.700	0.678	0.653	0.623	0.589	0.547	0.494	0.408	0.350	0.309	0.275	0.247	0.224	0.203	0.185	0.169
1.840	0.797	0.796	0.793	0.789	0.783	0.775	0.765	0.752	0.738	0.722	0.702	0.680	0.655	0.625	0.591	0.549	0.496	0.410	0.352	0.310	0.277	0.249	0.225	0.205	0.187	0.171
1.880	0.799	0.798	0.795	0.791	0.785	0.777	0.767	0.755	0.740	0.724	0.704	0.682	0.657	0.627	0.593	0.551	0.498	0.412	0.354	0.312	0.279	0.251	0.227	0.206	0.188	0.172
1.920	0.801	0.800	0.797	0.793	0.787	0.779	0.769	0.756	0.742	0.726	0.706	0.684	0.659	0.629	0.595	0.553	0.500	0.414	0.356	0.314	0.280	0.253	0.229	0.208	0.190	0.174
1.960	0.803	0.802	0.799	0.795	0.789	0.780	0.770	0.758	0.744	0.728	0.708	0.686	0.661	0.631	0.596	0.555	0.501	0.416	0.357	0.316	0.282	0.254	0.230	0.210	0.191	0.175
2.000	0.805	0.804	0.801	0.797	0.790	0.782	0.772	0.760	0.746	0.729	0.710	0.688	0.662	0.633	0.598	0.557	0.503	0.417	0.359	0.317	0.284	0.256	0.232	0.211	0.193	0.177

(c) Anode erosion experimental data

Energy Input (μJ)	Waveform parameter			Model			Experiment						error			
	T_{on}	I_a	V_a	h	d	Vol	h		d		Vol	h		d		Vol
	(s)	(A)	(V)	(μm)	(μm)	(μm^3)	(μm)	stdev	(μm)	stdev	(μm^3)	(μm)	(%)	(μm)	(%)	(%)
5	1.932E-07	0.879	21.840	0.922	6.698	16.651	0.819	0.218	7.206	0.960	16.992	0.103	12.521	0.508	7.046	2.010
12.5	2.977E-07	1.737	17.521	1.357	9.985	54.423	1.302	0.292	9.523	0.915	47.542	0.054	4.167	0.462	4.847	14.474
20	3.859E-07	2.063	27.109	1.741	11.997	101.163	1.497	0.557	11.574	1.031	80.510	0.244	16.279	0.424	3.661	25.653
27.5	4.321E-07	2.510	18.214	1.889	13.570	140.120	1.743	0.411	12.921	0.949	117.059	0.146	8.354	0.649	5.026	19.701
35	4.815E-07	2.997	24.320	2.031	14.218	165.575	2.014	0.415	13.443	1.260	147.226	0.016	0.811	0.775	5.762	12.463
42.5	5.140E-07	3.209	17.998	2.211	14.945	199.584	2.183	0.593	15.536	1.436	212.364	0.028	1.283	0.591	3.806	6.018
50	5.943E-07	3.296	18.671	2.595	16.923	300.976	2.384	0.478	16.439	2.032	260.116	0.211	8.829	0.485	2.947	15.708
Average													7.463		4.728	13.718

Note : Each value is taken from 20 experimental observations

APPENDIX B

CATHODE EROSION MODEL RESULTS

(a) PHSM Lookup table

β	γ	β	γ	β	γ	β	γ	β	γ	β	γ	β	γ	β	γ
0.01	15.826	0.51	0.224	1.01	0.075	1.51	0.030	2.01	0.012	2.51	0.005	3.01	0.002	3.51	0.001
0.02	7.868	0.52	0.218	1.02	0.073	1.52	0.030	2.02	0.012	2.52	0.005	3.02	0.002	3.52	0.001
0.03	5.215	0.53	0.213	1.03	0.072	1.53	0.029	2.03	0.012	2.53	0.005	3.03	0.002	3.53	0.001
0.04	3.889	0.54	0.207	1.04	0.071	1.54	0.029	2.04	0.012	2.54	0.005	3.04	0.002	3.54	0.001
0.05	3.093	0.55	0.202	1.05	0.069	1.55	0.028	2.05	0.011	2.55	0.004	3.05	0.002	3.55	0.001
0.06	2.563	0.56	0.197	1.06	0.068	1.56	0.028	2.06	0.011	2.56	0.004	3.06	0.002	3.56	0.001
0.07	2.184	0.57	0.192	1.07	0.067	1.57	0.027	2.07	0.011	2.57	0.004	3.07	0.002	3.57	0.001
0.08	1.900	0.58	0.187	1.08	0.066	1.58	0.027	2.08	0.011	2.58	0.004	3.08	0.002	3.58	0.001
0.09	1.679	0.59	0.182	1.09	0.064	1.59	0.026	2.09	0.011	2.59	0.004	3.09	0.001	3.59	0.000
0.10	1.502	0.60	0.178	1.10	0.063	1.60	0.026	2.10	0.010	2.60	0.004	3.10	0.001	3.60	0.000
0.11	1.357	0.61	0.174	1.11	0.062	1.61	0.025	2.11	0.010	2.61	0.004	3.11	0.001	3.61	0.000
0.12	1.237	0.62	0.170	1.12	0.061	1.62	0.025	2.12	0.010	2.62	0.004	3.12	0.001	3.62	0.000
0.13	1.135	0.63	0.166	1.13	0.060	1.63	0.024	2.13	0.010	2.63	0.004	3.13	0.001	3.63	0.000
0.14	1.047	0.64	0.162	1.14	0.059	1.64	0.024	2.14	0.010	2.64	0.004	3.14	0.001	3.64	0.000
0.15	0.971	0.65	0.158	1.15	0.058	1.65	0.023	2.15	0.010	2.65	0.004	3.15	0.001	3.65	0.000
0.16	0.905	0.66	0.155	1.16	0.057	1.66	0.023	2.16	0.009	2.66	0.004	3.16	0.001	3.66	0.000
0.17	0.847	0.67	0.151	1.17	0.056	1.67	0.023	2.17	0.009	2.67	0.004	3.17	0.001	3.67	0.000
0.18	0.795	0.68	0.148	1.18	0.054	1.68	0.022	2.18	0.009	2.68	0.003	3.18	0.001	3.68	0.000
0.19	0.748	0.69	0.144	1.19	0.054	1.69	0.022	2.19	0.009	2.69	0.003	3.19	0.001	3.69	0.000
0.20	0.706	0.70	0.141	1.20	0.053	1.70	0.021	2.20	0.009	2.70	0.003	3.20	0.001	3.70	0.000
0.21	0.668	0.71	0.138	1.21	0.052	1.71	0.021	2.21	0.009	2.71	0.003	3.21	0.001	3.71	0.000
0.22	0.634	0.72	0.135	1.22	0.051	1.72	0.021	2.22	0.008	2.72	0.003	3.22	0.001	3.72	0.000
0.23	0.603	0.73	0.132	1.23	0.050	1.73	0.020	2.23	0.008	2.73	0.003	3.23	0.001	3.73	0.000
0.24	0.574	0.74	0.129	1.24	0.049	1.74	0.020	2.24	0.008	2.74	0.003	3.24	0.001	3.74	0.000
0.25	0.547	0.75	0.126	1.25	0.048	1.75	0.020	2.25	0.008	2.75	0.003	3.25	0.001	3.75	0.000
0.26	0.523	0.76	0.124	1.26	0.047	1.76	0.019	2.26	0.008	2.76	0.003	3.26	0.001	3.76	0.000
0.27	0.500	0.77	0.121	1.27	0.046	1.77	0.019	2.27	0.008	2.77	0.003	3.27	0.001	3.77	0.000
0.28	0.479	0.78	0.119	1.28	0.045	1.78	0.019	2.28	0.007	2.78	0.003	3.28	0.001	3.78	0.000
0.29	0.460	0.79	0.116	1.29	0.045	1.79	0.018	2.29	0.007	2.79	0.003	3.29	0.001	3.79	0.000
0.30	0.441	0.80	0.114	1.30	0.044	1.80	0.018	2.30	0.007	2.80	0.003	3.30	0.001	3.80	0.000
0.31	0.424	0.81	0.111	1.31	0.043	1.81	0.018	2.31	0.007	2.81	0.003	3.31	0.001	3.81	0.000
0.32	0.408	0.82	0.109	1.32	0.042	1.82	0.017	2.32	0.007	2.82	0.003	3.32	0.001	3.82	0.000
0.33	0.393	0.83	0.107	1.33	0.042	1.83	0.017	2.33	0.007	2.83	0.003	3.33	0.001	3.83	0.000
0.34	0.379	0.84	0.105	1.34	0.041	1.84	0.017	2.34	0.007	2.84	0.003	3.34	0.001	3.84	0.000
0.35	0.366	0.85	0.103	1.35	0.040	1.85	0.016	2.35	0.007	2.85	0.002	3.35	0.001	3.85	0.000
0.36	0.353	0.86	0.101	1.36	0.039	1.86	0.016	2.36	0.006	2.86	0.002	3.36	0.001	3.86	0.000
0.37	0.341	0.87	0.098	1.37	0.039	1.87	0.016	2.37	0.006	2.87	0.002	3.37	0.001	3.87	0.000
0.38	0.330	0.88	0.097	1.38	0.038	1.88	0.016	2.38	0.006	2.88	0.002	3.38	0.001	3.88	0.000
0.39	0.319	0.89	0.095	1.39	0.037	1.89	0.015	2.39	0.006	2.89	0.002	3.39	0.001	3.89	0.000
0.40	0.309	0.90	0.093	1.40	0.037	1.90	0.015	2.40	0.006	2.90	0.002	3.40	0.001	3.90	0.000
0.41	0.300	0.91	0.091	1.41	0.036	1.91	0.015	2.41	0.006	2.91	0.002	3.41	0.001	3.91	0.000
0.42	0.290	0.92	0.089	1.42	0.035	1.92	0.014	2.42	0.006	2.92	0.002	3.42	0.001	3.92	0.000
0.43	0.282	0.93	0.087	1.43	0.035	1.93	0.014	2.43	0.006	2.93	0.002	3.43	0.001	3.93	0.000
0.44	0.273	0.94	0.086	1.44	0.034	1.94	0.014	2.44	0.006	2.94	0.002	3.44	0.001	3.94	0.000
0.45	0.265	0.95	0.084	1.45	0.034	1.95	0.014	2.45	0.005	2.95	0.002	3.45	0.001	3.95	0.000
0.46	0.258	0.96	0.082	1.46	0.033	1.96	0.013	2.46	0.005	2.96	0.002	3.46	0.001	3.96	0.000
0.47	0.250	0.97	0.081	1.47	0.032	1.97	0.013	2.47	0.005	2.97	0.002	3.47	0.001	3.97	0.000
0.48	0.243	0.98	0.079	1.48	0.032	1.98	0.013	2.48	0.005	2.98	0.002	3.48	0.001	3.98	0.000
0.49	0.237	0.99	0.078	1.49	0.031	1.99	0.013	2.49	0.005	2.99	0.002	3.49	0.001	3.99	0.000
0.50	0.230	1.00	0.076	1.50	0.031	2.00	0.013	2.50	0.005	3.00	0.002	3.50	0.001	4.00	0.000

(b) Cathode erosion experimental data

Energy input	Waveform Characteristic			Prediction		Experiment			error			
	T _{on}	V _a	I _a	R _m	Vol	R _m		Vol	R _m		Vol	
(μ J)	(s)	(V)	(A)	(μ m)	(μ m ³)	(μ m)	stdev	(μ m ³)	(μ m)	(%)	(μ m ³)	(%)
5	1.99E-07	31.618	0.778	0.741	0.851	0.799	0.074	1.066	0.058	7.938	0.215	20.190
12.5	2.94E-07	28.114	1.217	1.011	2.166	1.046	0.124	2.400	0.035	3.448	0.233	9.716
20	3.71E-07	28.266	1.612	1.310	4.711	1.254	0.161	4.131	0.056	4.211	0.580	14.049
27.5	4.32E-07	30.390	1.824	1.560	7.953	1.504	0.220	7.128	0.056	3.672	0.826	11.582
35	4.74E-07	28.852	2.116	1.702	10.320	1.733	0.243	10.903	0.031	1.847	0.583	5.346
42.5	5.26E-07	30.579	2.222	1.873	13.771	1.964	0.279	15.867	0.091	4.611	2.095	13.205
50	5.65E-07	29.395	2.408	1.950	15.528	2.152	0.314	20.871	0.202	9.704	5.344	25.603
Average										5.061		14.242

Note :

Each value of waveform characteristics is taken from 20 observations

Each value of R_m and Volume is taken from 54 observations

APPENDIX C

PULSE DISTRIBUTION STUDY RESULTS

(a) Study on the effect of machining depth setting to the pulse distribution

Electrode Size	Depth	ND	DD	Arcing	SC	Total
(μm)	(μm)	(%)	(%)	(%)	(%)	(%)
125	200	96.53	0.21	3.25	0.0000	100
	400	95.69	0.72	3.58	0.0000	100
	600	91.72	4.15	4.12	0.0000	100
	800	88.71	6.61	4.67	0.0012	100
average		93.16	2.93	3.91	0.0003	100
300	200	97.32	0.42	2.26	0.0000	100
	400	96.48	0.43	3.09	0.0013	100
	600	92.61	1.85	5.52	0.0258	100
	800	86.62	6.31	6.76	0.3043	100
average		93.25	2.25	4.41	0.0829	100

Note : each value is taken from 5 experimental observations

(b) Study on the effect of electrode feeding speed to the pulse distribution

Process	Electrode feeding speed	ND	DD	Arc	SC	Total
	($\mu\text{m/s}$)	(%)	(%)	(%)	(%)	(%)
Drilling	0.2	90.52	6.06	3.38	0.03	100
	0.5	86.51	6.39	6.76	0.33	100
	1	80.69	7.88	10.51	0.93	100
Milling	0.2	97.28	0.31	2.41	0.00	100
	0.5	95.62	0.52	3.86	0.0006	100
	1	77.08	9.42	13.42	0.0641	100

Note : each value is taken from 5 experimental observations

(c) Study on the effect of material removal rate and tool wear rate to the pulse distribution

Depth	ND	DD	Arc	SC	Material removal rate		Tool wear rate		Variation of Secondary Discharge	Variation of MRR	Variation of Tool Wear rate
(mm)	(%)	(%)	(%)	(%)	(mm ³ /s)	stdev	(mm ³ /s)	stdev	(%)	(%)	(%)
0.3	97.821	0.212	1.968	0.000	7.21E-06	3.22E-07	5.77E-07	3.14E-07	0.00	0.00	0.00
0.4	95.697	0.721	3.582	0.000	7.07E-06	3.14E-07	5.95E-07	2.30E-07	2.12	2.01	3.04
0.5	92.645	3.304	4.052	0.000	6.89E-06	3.56E-07	6.89E-07	3.14E-07	5.18	4.47	19.40
0.6	91.722	4.155	4.122	0.000	6.81E-06	2.98E-07	7.37E-07	4.13E-07	6.10	5.61	27.61
0.7	89.592	5.814	4.593	0.001	6.50E-06	3.63E-07	8.37E-07	3.57E-07	8.23	9.89	44.99
0.8	88.707	6.613	4.679	0.001	6.24E-06	4.10E-07	8.96E-07	4.78E-07	9.11	13.49	55.14
0.9	54.517	30.175	15.279	0.028	3.82E-06	5.33E-07	1.42E-06	7.28E-07	43.30	46.99	146.03

Note : each value is taken from 3 experimental observations

APPENDIX D

EROSION VOLUME ESTIMATION RESULTS

(a) Material removal estimation for Titanium workpiece material

Relation of C_{MR} with N_p

Energy input	Depth	Number of discharge pulse	Normal discharge	Delayed discharge	Arcing	Short circuit	V_{crater} anode average	V_{MR} prediction	V_{MR} experiment	estimation error
(μJ)	(μm)	(pulse)	(%)	(%)	(%)	(%)	(m^3)	(m^3)	(m^3)	(%)
5	300	2231196.5	98.84	0.98	0.18	0.00	1.29E-17	4.60E-12	5.41E-12	15.34
5	600	6040578.5	96.79	3.21	0.00	0.00	1.32E-17	1.13E-11	1.11E-11	3.61
5	900	13242671.5	80.12	19.73	0.15	0.00	1.30E-17	1.87E-11	1.74E-11	8.09
20	300	460202	99.08	0.79	0.13	0.00	5.54E-17	4.71E-12	5.58E-12	15.46
20	600	1132800	95.36	4.06	0.58	0.00	5.41E-17	1.00E-11	1.15E-11	12.99
20	900	2614926	82.38	17.45	0.18	0.00	5.21E-17	1.78E-11	1.95E-11	9.05
35	300	238207	100.00	0.00	0.00	0.00	1.32E-16	6.26E-12	6.19E-12	1.24
35	600	638721	99.74	0.17	0.09	0.00	1.26E-16	1.45E-11	1.27E-11	14.15
35	900	1063310	99.54	0.46	0.00	0.00	1.18E-16	2.16E-11	1.90E-11	13.61
50	300	146653	99.85	0.15	0.00	0.00	1.86E-16	5.66E-12	5.85E-12	3.39
50	600	391872	99.78	0.22	0.00	0.00	1.94E-16	1.43E-11	1.20E-11	19.67
50	900	687801	99.77	0.23	0.00	0.00	1.81E-16	2.23E-11	1.93E-11	15.27
average										10.99

(b) Material removal estimation for Nickel Alloy workpiece material Relation of C_{MR} with N_p

Energy input	Depth	Number of discharge pulse	Normal discharge	Delayed discharge	Arcing	Short circuit	V_{crater} anode average	V_{MR} prediction	V_{MR} experiment	estimation error
(μJ)	(μm)	(pulse)	(%)	(%)	(%)	(%)	(m^3)	(m^3)	(m^3)	(%)
5	300	2121171	94.77	5.24	0.00	0.00	1.05E-17	4.87E-12	4.48E-12	8.74
5	600	4605993	93.28	6.72	0.00	0.00	1.10E-17	1.08E-11	1.08E-11	0.56
5	900	9370014	73.36	25.56	1.09	0.00	1.05E-17	1.62E-11	1.99E-11	18.87
20	300	307296	100.00	0.00	0.00	0.00	5.68E-17	4.22E-12	5.23E-12	19.22
20	600	1042178	95.56	4.44	0.00	0.00	5.33E-17	1.25E-11	1.22E-11	2.62
20	900	1980218	87.33	12.56	0.11	0.00	5.22E-17	2.09E-11	1.87E-11	12.11
35	300	175658	100.00	0.00	0.00	0.00	1.08E-16	4.62E-12	5.35E-12	13.63
35	600	530234	100.00	0.00	0.00	0.00	1.04E-16	1.32E-11	1.24E-11	6.32
35	900	875447	99.94	0.00	0.06	0.00	1.05E-16	2.16E-11	2.12E-11	2.01
50	300	168956	100.00	0.00	0.00	0.00	1.56E-16	6.46E-12	6.53E-12	1.08
50	600	418080	100.00	0.00	0.00	0.00	1.57E-16	1.58E-11	1.38E-11	14.65
50	900	653272	99.80	0.13	0.01	0.00	1.46E-16	2.27E-11	2.12E-11	7.14
average										13.02

(c) Material removal and tool wear volume estimation for Ferrallium 255 workpiece

Energy input (μJ)	Depth (μm)	Number of discharge pulse	Normal discharge	Delayed discharge	Arcing	Short circuit	$V_{\text{crater anode}}$ average	V_{MR} prediction	V_{MR} experiment	estimation error	V_{crater} cathode average	V_{TW} prediction	V_{TW} experiment	estimation error
(μJ)	(μm)	(pulse)	(%)	(%)	(%)	(%)	(m^3)	(m^3)	(m^3)	(%)	(m^3)	(m^3)	(m^3)	(%)
5	300	3513640	99.00	1.00	0.00	0.00	1.36E-17	7.07E-12	5.38E-12	31.30	3.70E-19	3.95E-13	3.29E-13	19.99
5	600	7809616	98.47	1.19	0.26	0.09	1.35E-17	1.25E-11	1.17E-11	6.95	3.14E-19	8.84E-13	9.56E-13	7.54
5	900	12140260	70.65	28.72	0.63	0.00	1.30E-17	1.29E-11	1.46E-11	11.56	3.52E-19	1.58E-12	2.45E-12	35.49
20	300	718612	97.72	1.34	0.67	0.27	3.99E-17	6.58E-12	5.37E-12	22.46	2.27E-18	3.51E-13	4.44E-13	20.89
20	600	2197626	90.38	9.54	0.07	0.00	3.70E-17	1.29E-11	1.11E-11	15.85	1.94E-18	1.15E-12	9.37E-13	22.81
20	900	4229671	66.04	33.36	0.45	0.15	3.64E-17	1.62E-11	1.69E-11	4.02	1.87E-18	2.29E-12	2.50E-12	8.26
35	300	405509	98.07	0.64	0.86	0.43	5.69E-17	6.22E-12	5.65E-12	10.02	4.97E-18	3.82E-13	4.62E-13	17.16
35	600	940298	94.14	5.61	0.25	0.00	5.45E-17	1.06E-11	1.13E-11	6.09	4.77E-18	1.02E-12	1.10E-12	7.44
35	900	2366492	67.72	31.57	0.47	0.24	5.41E-17	1.61E-11	1.76E-11	8.35	4.37E-18	2.66E-12	2.33E-12	14.18
50	300	290168	99.43	0.38	0.19	0.00	6.31E-17	5.28E-12	5.62E-12	5.98	7.42E-18	3.76E-13	4.23E-13	10.98
50	600	623400	94.62	0.00	2.07	3.31	6.22E-17	9.37E-12	1.14E-11	18.18	9.94E-18	1.26E-12	9.64E-13	30.53
50	900	1468066	71.62	26.41	1.17	0.80	6.18E-17	1.36E-11	1.65E-11	17.39	6.94E-18	2.37E-12	2.06E-12	14.93
average										13.18				17.52

Note : Each value is taken from 2 observations

APPENDIX E

TOOL WEAR COMPENSATION RESULTS

	Normal Machining method		UWM		Proposed Method	
Target depth	Depth result	error	Depth result	error	Depth result	error
(μm)	(μm)	(%)	(μm)	(%)	(μm)	(%)
300	283.05	5.65	317.50	5.83	294.36	1.88
300	285.12	4.96	339.00	13.00	301.55	0.52
300	284.90	5.03	322.13	7.38	290.45	3.18
300	282.45	5.85	332.75	10.92	291.10	2.97
average	283.88	5.37	327.84	9.28	294.37	2.14
max	285.12	5.85	339.00	13.00	301.55	3.18
min	282.45	4.96	317.50	5.83	290.45	0.52
600	540.30	9.95	568.25	5.29	571.03	4.83
600	541.76	9.71	629.25	4.88	564.25	5.96
600	544.60	9.23	623.75	3.96	583.00	2.83
600	543.35	9.44	630.25	5.04	587.41	2.10
average	542.50	9.58	612.88	4.79	576.42	3.93
max	544.60	9.95	630.25	5.29	587.41	5.96
min	540.30	9.23	568.25	3.96	564.25	2.10
900	752.37	16.40	804.75	10.58	847.53	5.83
900	757.30	15.86	946.75	5.19	875.05	2.77
900	764.25	15.08	843.50	6.28	847.80	5.80
900	747.00	17.00	880.25	2.19	886.01	1.55
average	755.23	16.09	868.81	6.06	864.10	3.99
max	764.25	17.00	946.75	10.58	886.01	5.83
min	747.00	15.08	804.75	2.19	847.53	1.55

Statistical t-test result

n	Error on UWM (%)	Error on Proposed Method (%)
1	5.83	1.88
2	13	0.52
3	7.38	3.18
4	10.92	2.97
5	5.29	4.83
6	4.88	5.96
7	3.96	2.83
8	5.04	2.1
9	10.58	5.83
10	5.19	2.77
11	6.28	5.8
12	2.19	1.55

t-Test: Two-Sample Assuming Equal Variances

	<i>UWM</i>	<i>Proposed Method</i>
Mean	6.711666667	3.351666667
Variance	10.19370606	3.355251515
Observations	12	12
Pooled Variance	6.774478788	
Hypothesized Mean Difference	0	
df	22	
t Stat	3.162109893	
P(T<=t) one-tail	0.002258663	
t Critical one-tail	1.717144335	
P(T<=t) two-tail	0.004517327	
t Critical two-tail	2.073873058	

	CL = 95 %	CL = 99%	CL = 99.9%
t Critical	2.07	2.82	3.79
t Stat	3.16	3.16	3.16
Confidence Level	ok	ok	false