Development of in situ monitoring for micro-electrical discharge machining

Willy Kurnia

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Development of In Situ Monitoring for Micro-Electrical Discharge Machining

Willy Kurnia

School of Mechanical and Aerospace Engineering

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Abstract

With rapid technology advancement, the need for micro products is rapidly increasing in microelectronics, medical, automotive and telecommunication industries. Micro-Electrical Discharge Machining (EDM), the adaptation of conventional EDM, is an interesting way to realize micromachining process for the fabrication of three-dimensional complex microcomponents and microstructures from metallic and semiconductor substrate.

This research work focus on the development of a micro-EDM analytical model, which is essential to provide a good approximation of the material removal. This approximation will provide a good guide in choosing the appropriate process parameters. The model is based on an electro-thermal theory to estimate the geometrical dimensions of micro craters produced on the electrode and workpiece surfaces. The model incorporates voltage, current and pulse-on-time during material removal to predict the temperature distribution in the workpiece due to single discharges in micro-EDM. It is assumed that the entire superheated area is ejected from the workpiece surface while only a small fraction of the molten area is expelled. For verification purposes, single discharge experiments using a Resistor-Capacitor (RC) pulse generator are performed with pure tungsten as the electrode and AISI 4140 alloy steel as the workpiece. For the pulse-on-time range of up to 1000 ns, the experimental and theoretical results are found to be in close agreement. The average volume approximation errors are found to be 2.7% and 6.6% for the anode and cathode respectively.

An analytical model of the Micro-EDM process performances, namely Material Removal Rate (MRR), Tool Wear Ratio (TWR) and Surface Roughness (SR) are developed for the in situ monitoring of the machining process. The method is based on the crater geometry prediction using a developed theoretical model. Correction factors of removal, wear, and surface roughness are introduced in the approximation process to take into account the effects of undesirable discharges (open, short-circuit, arcing), machining time averaging error, overlapping craters, pockmarks, micro cracks, and reattachment of debris that result from the actual process. Based on the presented results, the analytical MRR approximation is able to provide a close approximation to the experimental results with up to 30% variation from the experimental MRR value. The analytical TWR presents a relatively better approximation with up to 24% variation from the experimental value. As for the SR

model, the average errors in the proposed models for Titanium in terms of R_a and R_t are found to be 6.56% and 4.5% respectively.

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List of Abbreviations

CNC	: Computer Numerical Control
DSS	: Data Dependent System
EDG	: Electrical Discharge Grinding
EDM	: Electrical Discharge Machining
EDWC	: Electrical Discharge Wire Cutting
FET	: Field Effect Transistor
GAME	: Gravity Assisted Micro EDM
HAZ	: Heat Affected Zone
HF	: High Frequency
MEMS	: Micro Electro Mechanical Systems
MRR	: Material Removal Rate
MST	: Micro System Technology
NEXUS	: Network of Excellence in Multifunctional Microsystems
PDE	: Partial Differential Equation
RC	: Resistor Capacitance
RF	: Radio Frequency
SEM	: Scanning Electron Microscopy
SI	: Surface Integrity
SR	: Surface Roughness
TWR	: Tool Wear Ratio
UWM	: Uniform Wear Method
WEDG	: Wire Electrical Discharge Machining

Nomenclature

α	: Average thermal diffusivity [m^2/s]
α'	: Adapted thermal diffusivity of the material [m^2/s]
a_R	: Non-black body of absorptivity
b	: Radius of the outer insulated cylinder [m]
C	: Combination of fraction of energy and fraction of molten area
C_a	: Combination of fraction of energy and fraction of molten area expelled in anode
C_c	: Combination of fraction of energy and fraction of molten area expelled in cathode
C_p	: Average specific heat [J/kg.K]
d	: Crater diameter [μm]
d_e	: The length of the electrode being eroded as tool wear [μm]
d_w	: The required depth of the hole to be machined [μm]
e	: Electron charge (1.6×10^{-19} Coulomb)
erf	: Error function
$erfc$	: Complementary error function
ε_0	: Permittivity [F/m]
E	: Complete elliptic integrals of the second kind
F_c	: Fraction of energy transferred to the cathode
F_p	: Fraction of energy input for plasma formation
λ	: Average number of particles dissociated out of the dielectric molecule
$ierfc$	: Inverse $erfc$
h	: Crater depth [μm]
H	: Enthalpy [J]
I	: Discharge current [A]
I_a	: Average current [A]
I_p	: Peak current [A]
J_0	: Bessel function of the first kind of the zero order
J_1	: Bessel function of the first kind of the first order
K	: Complete elliptic integrals of the first kind

K_t	: Average thermal conductivity [W/m.K]
l	: Depth of the material [m]
m	: Latent heat of melting [kJ/kg]
m_i	: Mass of particle [kg]
M	: Mach number
n_{se}	: Ion density [m ⁻³]
P	: Pressure [bar]
P_o	: Ambient pressure [bar]
q	: Heat flux [W/m ²]
θ_{crater}	: Crater's edge temperature
r	: Radial distance from the origin [m]
r_{crater}	: Crater radius [m]
r_e	: The radius of the electrode [μ m]
r_g	: The disk heat source radius [m]
r_o	: Radius of insulated surface of the workpiece [m]
r_w	: Radius of the hole to be machined [μ m]
R	: Heat flux radius [μ m]
R_a	: Center line average surface roughness [μ m]
R_{anode}	: Heat flux radius at anode [μ m]
$R_{cathode}$	: Heat flux radius at cathode [μ m]
R_f	: Outer radius of dielectric in the gap [m]
R_p	: The plasma radius [μ m]
R_t	: Maximum peak to valley surface roughness [μ m]
S_{MRR}	: Removal factor
S_{Ra}	: Correction factor for the theoretical R_a
S_{Rt}	: Correction factor for the theoretical R_t
S_{TWR}	: Wear factor
S_y	: The yield strength of the anode material [MPa]
ρ	: Average material density [kg/m ³]
t	: Time [s]
t_d	: Pulse-on-time [ns]

t_m	:	Total time per discharge [s]
t_{off}	:	Pulse-off-time [s]
t_t	:	Total machining time [min]
σ	:	Stefan-Boltzmann constant ($5.670 \times 10^{-8} \text{ JK}^{-4} \text{ m}^{-2} \text{ s}^{-1}$)
T	:	Temperature [K]
T_e	:	Electron temperature [K]
T_i	:	Initial temperature [K]
T_m	:	Melting temperature [K]
T_o	:	Ambient temperature [K]
V_a	:	Average voltage [Volts]
V_{crater}	:	Crater volume [μm^3]
V_{el}	:	Total volume removed from the electrode [μm^3]
$V_{electrode}$	:	Crater volume removed from the electrode per discharge [μm^3]
V_o	:	Open voltage [Volts]
$V_{workpiece}$	:	Crater volume removed from the workpiece per discharge [μm^3]
V_{wp}	:	Total volume removed from the workpiece [μm^3]
z	:	Vertical distance from the origin [m]

List of Publications

1. Kurnia, W, Yeo, S.H., and Tan, P.C., *Development of In-situ Monitoring and Control of Micro-EDM Process*. 8th Field Wise Seminar on Manufacturing Engineering, Vientiane, Laos: 21-22 December 2006.
2. Yeo, S.H., Kurnia, W., and Tan, P.C., *Electro-thermal Modelling of Anode and Cathode in Micro-EDM*. Journal of Physics D: Applied Physics, 2007. **40**(8): p. 2513-2521.
3. Yeo, S.H., Kurnia, W., Tan, P.C., and Wong, M., *Development of In-situ Monitoring and Control of Micro-EDM Process*. 35th International MATADOR Conference, Taipei, Taiwan: 18-20 July 2007.
4. Yeo, S.H., Tan, P.C., and Kurnia, W., *Effects of powder additives suspended in dielectric on crater characteristics for micro electrical discharge machining*. Journal of Micromechanics and Microengineering, v 17, n 11, Nov 1, 2007, p N91-N98.
5. Yeo, S.H., Kurnia, W., Tan, P.C., *Critical Assessment and Numerical Comparison of Electro Thermal Models in EDM*. Journal of Materials Processing Technology (accepted for publication, 8 October 2007).

CHAPTER 1

INTRODUCTION

1.1 Background

With rapid technology advancement, the need for micro parts and micro products is rapidly increasing in microelectronics, medical, automotive and telecommunication industries. Fig. 1.1 shows the growth of Micro System Technology (MST) based on the market study done by Network of Excellence in Multifunctional Microsystems (NEXUS) covering the period from 2004 to 2009. Over the next five years, this market is predicted to grow at a rate of 16% per year from US\$12 billion in 2004 to US\$25 billion in 2009 across a spectrum of 26 MEMS/MST products [1]. Therefore, the development of manufacturing techniques to match this global demand in micro parts and micro products in terms of manufacturability, accuracy and repeatability is extremely important.

Fig. 1.1 Total market for 26 MST/MEMS products, 2004-2009 [1]

There are many micromachining techniques such as micro drilling, micro milling, laser machining, focused ion beam, and lithography. Each technique has its own merits and limitations in fabricating micro parts to meet the required specifications. For example, it is very difficult to machine three dimensional structures due to its machining characteristics, i.e. lithography. In addition, for some techniques, sculptured machining is almost impossible.

Electrical Discharge Machining (EDM) is a machining technique which is able to overcome these difficulties. It is one of the non-conventional material removal processes that employ electro-thermal effects to machine electrically conductive materials. The major advantages of EDM process are as follow:

- 1. Capability to machine any material regardless of its hardness.
- 2. Burr-free machining.
- 3. Negligible force interaction between the tool and the workpiece.
- 4. Capability to machine complex 3D structures.
- 5. Cavities with thin walls and fine features can be produced.

As material removal is realized without physical contact between the tool and workpiece, the force exerted onto the workpiece is insignificant, making EDM especially suited for the fabrication of micro-scale features. In addition, the application of EDM has become more viable due to the introduction of more sophisticated CNC systems and spark generators that help to improve the machined surface quality. Therefore, this technique is adapted in micromachining processes as micro-EDM.

Interest in micro-EDM has generated a significant amount of research into improving its machining performances, such as Material Removal Rate (MRR), Tool Wear Rate (TWR), and Surface Roughness (SR). The major research interest areas in micro-EDM are shown in Fig. 1.2.

Fig. 1.2 Major research interest in micro-EDM problematic areas [2]

Although many studies have been conducted to address these problematic areas, the outcomes in terms of geometrical accuracy, machining time and surface quality are still far from satisfactory. Therefore, new concepts and research approach are highly essential in order to fully utilize the capability of micro-EDM processes in producing micro scale features.

In this research work, attempts have been made to monitor the micro-EDM process in real-time based on the crater dimensional geometry calculation using a developed theoretical micro-EDM model. The model is able to predict the crater geometry of the anode and cathode numerically using the electrode properties, the average voltage, the average current and the pulse-on-time data obtained during the material removal process. The crater geometries are then used to calculate and monitor the analytical MRR, TWR, and SR; since the values are highly dependent on the craters resulted during each discharge. The analytical TWR monitoring results are then used in the tool wear compensation method to ensure the geometrical accuracy of the machined parts. The outcome of this approach will greatly elevate the advancement of micro-EDM.

1.2 Motivation

Micro-EDM is an interesting micromachining process for the fabrication of three-dimensional complex microcomponents and microstructures from metallic and semiconductor substrates [3]. However, the MRR is relatively low as compared to the other micro-machining techniques. In addition, the occurrences of tool wear which lead to a lack of machining accuracy in the geometry of the workpiece has become the major setback for this process. The requirements of high accuracy in the machined feature are more demanding since minute imperfections are magnified in the micro scale.

To improve MRR and reduce the influence of tool wear, it is necessary to monitor the process in real time and apply more precise control on the process parameters. An online monitoring system capable of directly retrieving the information of the process performance from the discharge gap has to be implemented for both process and machining performance controls. This system can be used as a command centre for controlling parameters such as pulse energy, gap distance and electrode movement. An attempt in this direction is proposed in this research work. The outcome of the research

work in this area will improve the micro-EDM process in terms of the process performance monitoring and machining accuracy.

1.3 Objective

The objectives of the research work are:

1. To study the relationship between process parameters and process performance of micro-EDM.
2. To develop a reliable analytical model for micro-EDM process.
3. To establish a novel in situ monitoring system for micro-EDM process.
4. To improve the tool wear compensation technique using in situ monitoring results.

1.4 Scope of work

This research work envisages a novel micro-EDM process monitoring which has the capability to observe the process performance in real time in terms of Material Removal Rate (MRR), Tool Wear Ratio (TWR), and Surface Roughness (SR). This is done by directly retrieving the process information from the discharge gap between the electrode and the workpiece using the voltage and current probes. These data are then used in the micro-EDM theoretical model to predict the crater geometries which in turn are used to determine the process performance.

The first step of this research work is a thorough study to understand the relationship between the process parameters (voltage, current, pulse-on-time, and gap distance) and the process performance of micro-EDM using single discharge experiments. The single discharge experimental rig was specifically built using an ultraprecision positioning system and a specially developed RC pulse generator. This work is extended by using the data obtained for the development of the analytical model for micro-EDM process. The analytical model is then validated using another set of single discharge experiments.

The second step of the research work is the implementation of the micro-EDM theoretical model in the actual micro-EDM machine to predict the crater dimensional geometry. The results are then used to develop an analytical model for the monitoring of MRR, TWR, and SR. The validation of the analytical model using experimental results is carried out.

This work involves numerical simulation using commercially available mathematical software (MATLAB™ 7.0) to calculate the crater size for one discharge cycle. The characterization of the experimental work is done by using equipment such as Scanning Electron Microscopy (JEOL™ JSM-5600), white light interferometer (WYKO™ NT2000), PLμ confocal imaging profiler (SensoFar™), and optical microscope (ROI OMIS II™). The commercial micro-EDM machine from Panasonic (MG-ED72W™) is used to develop the novel in situ monitoring system.

1.5 Outline of thesis

The following list describes the outline of the thesis:

- Chapter 1: INTRODUCTION

This chapter covers the basic explanation of Electrical Discharge Machining (EDM), the motivation, objectives, scope and the report layout.

- Chapter 2: LITERATURE REVIEW

A critical literature review is covered in this chapter. The literature review will cover the working principle and technology advancement of EDM process, especially in micro-EDM.

- Chapter 3: APPROACH TO IN SITU MONITORING AND EXPERIMENTAL METHODOLOGY

The approach method, experimental set up and experimental procedure are explained in this chapter. All the equipment used in the experiments is described briefly.

- Chapter 4: ELECTRO-THERMAL MODELLING OF MICRO-EDM PROCESS

The development of analytical micro-EDM model is covered in this chapter. This chapter starts with the numerical analysis and comparison of the existing models. Next, the theoretical model is developed using a two dimensional heat transfer for a material subjected to a disk heat source on its surface. The validation of the model using experimental results is also explained.

- Chapter 5: IN SITU MONITORING OF MICRO-EDM PROCESS

This chapter provides the rationalization of the main objective for this research project. The development of in situ process monitoring for micro-EDM and its working principle is covered. Experimental validations are also provided to study the consistency of this method in terms of MRR, TWR, and SR monitoring results.

- Chapter 6: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This final chapter of the thesis describes the concluding summary of the research work. Finally, the explanation of the future research work is presented.

CHAPTER 2

LITERATURE REVIEW

This chapter presents the state-of-the-art literature review of the cited research work. In the first section, a brief history of EDM process is given. The second section provides the introduction of the EDM process. The technology and trends in micro-EDM are presented on the third section. Finally, the last section summarizes the outcome of the literature review. The presentation flow of the literature review is illustrated in Fig. 2.1.

Fig. 2.1 Literature review document map

2.1 Brief history of EDM Process

Electrical Discharge Machining (EDM) and Electrical Discharge Wire Cutting (EDWC) are known to be the most widely used non conventional machining techniques in production, job shops, and in tool rooms. Its basis can be traced as far as 1770 when English chemist Joseph Priestly discovered the erosive effect of electrical discharge [4]. However, the volume of the workpiece and electrode material removed during the process is about the same, making it difficult to be utilized efficiently.

In 1941, The Union of Soviet Socialist Republics (USSR) government assigned Moscow University Professors, Dr. Boris Lazarenko and Dr. Natalya Lazarenko, at the All Union Electro Technical Institute to investigate whether the life of the engine distributor-breaker points could be extended by suppressing the number of sparking on the components [5]. The experiment itself was unsuccessful because it did not develop a means for extending the life of the automotive breaker points due to sparking. Their experiments led to further investigations that indicated metals could be shaped by electrical discharge. In 1943, the Lazarenkos developed a spark-machining process with an electrical circuit that used many of the same components as the automobile ignition system. The principle of the discharge generator used in the circuit has been employed over many years in power supplies for EDM machines and, in an improved form, is still used today in certain application.

After more than 60 years since the first development of EDM, the machine has been significantly improved through the work of many researchers. Progress has been made since the use of Resistor Capacitance (RC) circuit generator and vacuum tubes to solid state-transistors with nanosecond pulsing. The control system has also developed from manual electrode control to automatic Computer Numerical Control (CNC). In the late of 1960, wire-cut EDM is developed as the result of seeking a technique to replace the machined electrode in EDM, even though it had already been suggested as a process variant in 1949 [6]. Only after 1990, Prof. Masuzawa successfully brought EDM into play in micromachining processes, known as micro-EDM [7, 8].

2.2 EDM Process

EDM is the process of machining by using precisely controlled sparks that occur between an electrode and a workpiece in the presence of a dielectric fluid. The electrode, usually referred as the cutting tool, does not have physical contact with the part being machined. Instead, the electrode is kept at a certain distance from the workpiece. Within the process, the electrical energy from a pulse generator is turned into thermal energy to vaporize and melt the material at the surface of each pole. The EDM basic schematic diagram is shown in Fig. 2.2.

Fig. 2.2 Basic schematic of an EDM system

Only electrically conductive materials can be machined by using EDM. Electrode materials must also be electrically conductive. Dielectric used in EDM is usually liquids, commonly hydrocarbon oil, silicone-based oil, and distilled or deionized water [9, 10]. In some instance, gas dielectric is used [11]. The dielectric initially acts as an insulator until ionization occurs and it becomes conductive in the area where the spark occurs. The capability of the EDM process and the producible geometries are shown in Table 2.1.

Table 2.1 Product forms and corresponding EDM processes [12]

Form of electrode	EDM Process	Form of product						
		Hole		3D		Solid body		Slot
		Square	Round	Cavity	Convex	Round	Square	
Cylinder, pipe	Drilling, milling		⊕	⊕				
Rectangular rod	cavity-sinking, milling	⊕		⊕				
Block, fixed	EDG					⊕	⊕	
Disk, plate	EDG, cavity-sinking							⊕
Wire	WEDM	⊕	⊕		⊕	⊕	⊕	⊕
3D form	cavity-sinking			⊕				

2.2.1 Working Principle

The working principle of EDM process is illustrated in Fig. 2.3. The dielectric strength is the main factor which affects the occurrence of spark. This parameter depends on the dielectric type and the gap distance. Fig. 2.3 (a) shows the condition where the energy input is inadequate to breakdown the dielectric due to the large gap distance. This condition is usually referred as “open gap” and no sparks occur inside the gap.

Fig. 2.3 Spark sequence in EDM process [13]

The spark will only occur when the electrical voltage input applied is large enough to breakdown the dielectric, either by increasing the input voltage or by closing the gap distance. The method commonly used is by closing the distance. The electrode is traversed to the workpiece while the voltage input remains constant until the distance is adequate for the applied energy to breakdown the dielectric. The breakdown will occur at the closest asperity between the electrode and the workpiece, where the electrical field intensity is at maximum. The electromagnetic field will be created and the dielectric within this field will be polarized as the resistance decreased. This sequence is illustrated in Fig. 2.3 (b) and (c). The cathode will emit electrons while the anode will emit ions. The mass of an electron is 9.11×10^{-31} kg and the mass of an ion is 1.67×10^{-27} kg. Because of this difference, the ions move very slowly as compared to the electrons and 95% of the current will be carried by the electrons [14]. As the current increases, the voltage will decrease.

The electrons will collide with the neutral particles in between the electrode and the workpiece. It will split the neutral particles into positive and negative charged particles, known as ionization process. The dielectric fluid becomes heated from the flow of electricity and then change into a gas known as plasma which acts as a channel for the current flow. The plasma has a very high temperature and enclosed within a high pressure sheath of gases. It was reported that the temperature of this plasma range from 7000 K to as high as 40000 K [14-17] and the plasma pressure rises rapidly as much as 200 atm [18]. Electrons and ions continuously migrate to the anode and cathode respectively at a very high current density, creating a column of vapor between the two poles. During this process, the localized melting and vaporization of the electrode and the workpiece occur. This sequence is depicted in Fig. 2.3 (d).

In Fig. 2.3 (e), the plasma channel continues to expand rapidly while the temperature and pressure increased substantially. The vaporized and molten area of the electrode and the workpiece is held in place by the pressure of plasma channel. At the end of this sequence, the power input is switched off. The voltage and current will suddenly drop to zero and the plasma channel collapses upon removal of the heat source, as illustrated in Fig. 2.3 (f). The dielectric will rush to fill the collapsed channel and portions of molten material from the electrode and the workpiece will be expelled from the surface. The sudden drop in temperature due to the dielectric rush will cause the solidification of the remaining molten

materials. A micro crater is thus created on the surface of the electrode and the workpiece, as shown in Fig. 2.3 (g).

The ejected molten material will become debris which is trapped in between the electrode and workpiece. Fresh dielectric will flush the debris away from the gap and help the recovery of the dielectric strength. The electrical input is kept in off state until a certain time to ensure the recovery of the dielectric strength. This is a necessary step in EDM to prevent arcing which can damage the surface of the electrode and the workpiece. This sequence is depicted in Fig. 2.3 (h).

2.2.2 Micro-EDM

Micro-EDM is a specific type of EDM process. The term micro is used if the size of the products or structural details is smaller than 500 μm . The machined geometry can be holes [19, 20], cavities [21], or grooves [22]. The micro-EDM system is developed from conventional EDM system by reducing the discharge energy and enhancing the positioning accuracy. The working principle of micro-EDM is similar with conventional EDM. The differences between these two are summarized in Table 2.2.

Table 2.2 Comparison between micro-EDM and conventional EDM [2]

Conventional (macro) EDM	Micro-EDM
Usually used to machine large hole or pocket (>500 μm)	Usually used to machine small hole or pocket (< 500 μm)
The gap distance between the electrode and the workpiece is large (> 10 μm)	The gap distance between the electrode and the workpiece is extremely small (< 10 μm)
Large pulse-on-time (> 1 μs)	Small pulse-on-time (< 1 μs)
High Material Removal Rate	Low Material Removal Rate
Erosion rate is maximized within the allowable surface tolerances	Surface roughness is optimized within the erosion rate tolerances
Workpiece and electrode handling is simple	Workpiece and electrode handling is hard due to the size and the accuracy should be high
The requirement of tool (electrode) precision and the clamping system (repeat accuracy) is not high	The requirement of tool (electrode) precision and the clamping system (repeat accuracy) is very high ($\sim 1\mu\text{m}$)

In comparison with the other micromachining techniques, micro-EDM has unique features which make it one of the most powerful methods for fabricating micro holes in metal and in other electrically conductive materials. The advantages of this process are listed as follow:

- 1. Complicated contour can be manufactured in a single operation.
- 2. High geometrical accuracy.
- 3. Applicable for any`` conductive materials regardless of its hardness.
- 4. Capable to machine structures with high aspect ratio.
- 5. Non-contact process, suitable for fragile workpiece.
- 6. Small Heat Affected Zone (HAZ).
- 7. Burr free machining.
- 8. Precision of submicron order is possible.

Table 2.3 Achievable workpiece accuracy of micro-EDM [12]

	Wire EDM	Micro cavity-sinking EDM
Form deviation [μm]	± 1	± 2
Positional deviation [μm]	< ± 1	< ± 1
Average surface roughness Ra [μm]	0.1-0.2	0.2-0.3
Average peak to valley height Rz [μm]	0.5-2.5	1-5
Minimum structure width:		
Webs [μm]	20-40	20-40
Grooves [μm]	50-60	20-40
Maximum aspect ratio:		
Webs	20-30	15-25
Grooves	50-60	10-25
Hole	-	10-25
Internal radius [μm]	20	10
Smallest electrode dimension [μm]	30	10

Due to its process characteristics, micro-EDM is predominantly applied for the micro fabrication of metallic component. The capabilities of micro-EDM process can be seen from the achievable accuracy of the process in Table 2.3.

2.2.3 Process Parameters

Process parameters are the input variables which affect the outcome of micro-EDM process. The selection of process parameters was traditionally based on experiences or handbook values, which produced inconsistent machining performances. However, optimization now relies on process analysis to identify the optimum value for each parameter to achieve the desired machining characteristic.

A grey relational analysis is proposed [23] to solve the complex relationships between process parameters and process performances of micro-EDM. Taguchi method is applied to improve MRR by introducing high carbon content to the electrode prior to the normal sparking process [24]. In addition, fuzzy logic [25] and dynamic signal-to-noise ratio (S/N) to classify the process parameters [26] are used to optimize the process performances.

2.2.3.1 Electrical Process Parameters

The electrical process parameters in micro-EDM are:

1. Pulse-on-time

Pulse-on-time is the time in which the machining process occurs. This parameter is characterized by the voltage and current waveforms. It starts when the dielectric is broken down into ionized state and the current starts to flow through the discharge gap. The longer the pulse-on-time, the higher is the MRR, TWR, and SR due to higher energy input to the discharge gap. Higher pulse-on-time also creates more micro cracks on the workpiece surfaces [27]. Fig. 2.4 illustrates qualitatively, the maxima in the erosion rate versus pulse-on-time curves for the anode (Cu) and cathode (Fe), with crossover at about 0.5 μ s. Although different combinations of anode and cathode materials will give different quantitative values of pulse-on-time and erosion rate, it generally has the same trend with this curve.

Fig. 2.4 The anode and cathode erosion rate with pulse-on-time [28]

2. Pulse-off-time

Pulse-off-time is defined as the time from the end of the pulse-on-time until the start of the next dielectric breakdown due to the next electrical pulse energy transmissions to the discharge gap. This parameter is necessary to ensure that the dielectric has enough time to recover its dielectric strength in order to prevent arcing.

3. Voltage

This parameter is directly related to the energy input. Higher voltage will cause the dielectric to breakdown more easily. Higher voltage will cause higher MRR and TWR until a certain point where it reaches a maximum value and additional increase in voltage will reduce MRR and TWR. However, when the parameter is compared with discharge current, the effect of voltage on MRR and TWR is not significant.

4. Current

As in voltage, current is also directly related to the energy input. This parameter is usually kept around 1-5 Amperes in micro-EDM. Higher current will result in higher MRR and TWR.

5. Polarity

Polarity is the connection between the positive and negative side of the pulse generator to the electrode and the workpiece. Experimental results show that the phenomenon occurring in the anode and cathode during the discharge process is

different in terms of the diameter and depth of the crater, the total energy used, duration of pulse-on-time, MRR, and SR. In general, the material removal rate (MRR) for cathode is larger than anode [29]. It was also shown that in large pulse-on-time; the material removal from the anode is almost negligible as compared to the cathode [28]. For the anode, the crater depth is shallow and flat, where; on the other hand, the crater in the cathode is deeper and have a hollow near the center and a projection at the circumference [30]. Therefore, the surface roughness for anode is generally better than cathode.

2.2.3.2 Non-electrical Process Parameters

Non-electrical parameters play a critical role in the process performance of micro-EDM. The descriptions of each parameter are as follow:

1. Electrode and workpiece material

Material properties have a very significant effect on the MRR, TWR and SI. In general, material with high melting temperature is preferred as an electrode due to its low TWR. In addition, the workpiece and electrode combination also affects process performance. It was shown that the combination between copper electrode with EN-31 (SAE 52100, 100Cr6) as the workpiece offers higher MRR, lower TWR, better SR, and higher accuracy as compared to aluminium, copper tungsten or brass [31].

2. Dielectric fluid

Formations of sparks, erosion properties of tool and workpiece electrodes, mechanical and metallurgical properties of machined components are determined partly by the discharging medium. Properties of dielectric liquid affects the machining performance by changing the discharging conditions at the spark gap [32-34]. Thus the choice of dielectric plays an important role in the EDM process. The effect of kerosene and distilled water on MRR and TWR are shown in Fig. 2.5.

Fig. 2.5 The influence of dielectric type on MRR and TWR [35]

3. Flushing

Flushing is a technique to remove the debris from the discharge gap and recover the dielectric strength of the fluid, which is very important to prevent arcing. It was shown that the flushing affects MRR and TWR in roughing process, while in finishing operation, it affects SI [36].

Various methods have been applied to create a good flushing condition in the discharge gap for conventional EDM such as forced flushing, jet flushing, immersion flushing and modification of the tool electrode [13, 37]. However, most of the methods are inapplicable to micro-EDM due to the limitations on the small electrode sizes and induced vibration. In order to achieve a good flushing condition in micro-EDM, some variations such as rotary motion of the electrode or the workpiece [38-40], ultrasonic vibration [41-43], magnetic field flushing [44], and gravity assisted flushing [45] have been reported.

2.2.4 Process Performances

2.2.4.1 Material Removal Rate (MRR)

The MRR is a ratio between the volume of material removed from the workpiece and the total machining time, as given in equation (2.1).

$$\text{MRR} = \frac{\text{Volume of material removed from the workpiece}}{\text{Total Machining time}} \tag{2.1}$$

Various methods have been employed by many researchers to improve MRR. The common approach is by changing the process parameter of micro-EDM. Another promising MRR improvement technique has also been made by using multi-electrode with independent electrical connection to perform a discharge separately from each electrode [46]. An oxygen assisted EDM system was also found to be very useful in improving MRR [47].

2.2.4.2 Tool Wear Ratio (TWR)

TWR is a parameter to represent the volumetric wear occurring in the electrode. It is define as the ratio between the material volume removed from the electrode (V_{el}) and the material volume removed from the workpiece (V_{wp}), as shown in equation (2.2).

$$TWR = \frac{V_{el}}{V_{wp}} \tag{2.2}$$

Similar to MRR, TWR is commonly improved by changing the process parameter setting.

2.2.4.3 Surface Integrity (SI)

In EDM process, SI represents several factors, namely the size of the crater, SR, micro hardness, micro cracks, residual stresses, depth of the recast layer, and depth of HAZ. Among these factors, the most commonly used is SR. This is because among those factors, SR is the easiest to measure and the measurement time is short.

During the micro-EDM process, a very high temperature causes metallurgical changes in the surface layer of the workpiece. The surface is made up of three distinctive layers consisting of recast layer, HAZ, and parent material, as shown in Fig. 2.6.

Fig. 2.6 Surface layer of EDM process [48]

In general, grain boundary weaknesses are accentuated and micro cracking usually occurs due to the residual stress [49]. A thin recast layer of 1 μm at 5 μJ discharge energy to 25 μm at high discharge energy is formed [50]. Some annealing of the workpiece can be expected in a zone just below the machined surface. The hardening of the surface layer during EDM process imparts a better wear resistance characteristic. However, it will reduce the fatigue strength of the products due to micro cracks which are developed in the surface layer [51].

Various methods of improving SI have been reported. A composite electrode with low thermal conductivity is used to allow the composite material from the electrode to deposit onto the workpiece surfaces, producing less crack as well as high corrosion and wear resistance [52, 53]. Recently, powder suspended particles were used to improve SI by creating higher charge probability and lowering the breakdown strength of the dielectric [54].

The effects of EDM process parameters on SR has been reported by Keskin et al. [55] and Lee and Li [56]. An empirical approximation to estimate the surface roughness from the logarithmic trend of the experimental results based on the discharge energy has been used by Jeswani [33, 57]. In addition, SR approximation by least-square equations of the third degree where the maximum variation between the calculated and measured value was found to be 43% and 55% for St37 and 100Cr6 respectively [58]. Based on the design of experiments method, an empirical equation of surface roughness using power, pulse time, and spark time parameters was reported [55]. The statistical multi-parameter approach to investigate surface finish of Ck60 steel plates has been studied [59].

Although the abovementioned empirical models presented a reasonable agreement with the conventional EDM experimental data, the results were in poor agreement for different electrode materials and polarity since the material properties and the polarity settings were not considered in the models. An approach in this direction was proposed using neural-network models and a neuro-fuzzy network model [60]. A semi-empirical model based on dimensional analysis was subsequently developed using peak current, pulse duration, polarity, and material properties [61]. The average error between the experimental results and the model predictions in conventional EDM were found to be up to 11.45%.

A model to predict the surface roughness of micro-EDM machined surface based on the configuration of a hemispherical single-spark cavity has been reported Kiran and Joshi

[62]. By assuming the normal distribution of surface heights, the surface roughness values were calculated. The effect of debris on the surface roughness values was also investigated.

2.3 Technology and Trends in Micro-EDM

This section focuses on the current trend in micro-EDM process. Starting from a general view of problematic areas in micro-EDM process, it then focuses on more specific details on micro-EDM analytical models and micro-EDM process monitoring and control.

2.3.1 Problematic Areas in Micro-EDM Process

Despite the large number of publications which have been reported, there are some areas in micro-EDM which are still not sufficiently solved. A review on the recent application of micro-EDM and identified problematic areas within those applications has been reported [2] (see Fig. 1.2). Similarly, the state of the art on EDM process has been reported [63].

Their results show that the research works on EDM can be classified into:

1. Optimizing the process variables.
2. Monitoring and control the process.
3. Improving the process performance.
4. EDM developments.

As shown in Fig. 2.7, the published works on EDM process have been focused on the improvement of process performance. The number of works on process monitoring and control are limited as compared to the other topics. This distribution shows that the works on the process performance improvement, process variables optimization, and EDM machine development are more intense than the process monitoring and control. However, the advancement of these three topics will eventually require more advance process monitoring and control due to the need of highly reliable EDM servo system.

Fig. 2.7 Distribution of the collected EDM research publications [63]

2.3.2 Analytical Model of the EDM Process

Various researchers have investigated the analytical modeling of EDM process since 1971. Due to the process characteristics, the modeling can be divided into three sections:

- 1. Plasma channel modeling.
- 2. Anode erosion modeling.
- 3. Cathode erosion modeling.

Fig. 2.8 shows the three sections of the EDM analytical models. The energy input into the EDM process from the pulse generator will be divided among the plasma channel formation, cathode erosion, and anode erosion.

Fig. 2.8 Three sections of EDM analytical models

2.3.2.1 Plasma Channel Modeling

The modeling of plasma channel formation is necessary to define the boundary condition for anode and cathode erosion models. Two approaches have been reported by several authors:

1. Fluid dynamics approach

In the fluid dynamics approach, the plasma formation and its state at any time were defined by using fluid dynamics, heat transfer, and state equations. Therefore, the growth of plasma is contained in the equations. The first comprehensive attempt to model the plasma channel was done by Van Dijck et al. [64, 65]. It was suggested that the plasma expands with a constant mass throughout the process. The continuity and momentum equation were used to develop the model. The power distribution calculation using an emission electron theory showed that only about 10% of the energy input was used in the plasma formation. However, the plasma was taken as adiabatic and perfect gas heat capacities are used without including the heats of dissociation and ionization. As a result, plasma temperature was not considered in the model and the plasma pressure was underestimated, less than 1 bar above ambient pressure.

Following this approach, Lhiaubet et al. [66] extended the equation by taking the properties of diatomic plasma as constant and include the fluid dynamic equations

in the plasma models. The perfect gas assumptions were still used and the heats of disassociation and ionization were neglected. Consequently, the plasma temperature and the pressure changed rapidly to be over one million Kelvin and under 10 bar after 25 μ s for a maximum current level of 250 A. Eubank et al. [67] reported variable mass cylindrical plasma which expands with time. The plasma is considered to have uniform macroscopic properties which interface directly with the ambient dielectric liquid. During the formation, radiation from the plasma vaporizes, dissociates, and ionizes a thin cylindrical shell of liquid and turns it into plasma, as shown in Fig. 2.9.

Fig. 2.9 Schematic diagram of plasma expansion process [67]

The plasma radius will then increase in time due to the high pressure inside the plasma and the transformation of dielectric to plasma at the interface. A simple unsteady-state energy balance was given by Eubank et al. [67] with the plasma as the thermodynamic system:

$$VIF_p = (H - H_0) \left(\frac{dm}{dt} \right) + m \left(\frac{dH}{dt} \right) \quad (2.3)$$

where, V is voltage (V), I is current (A), F_p is fraction of energy input for plasma formation, H is enthalpy (J), m is mass (kg) and t is time (s). Following equation (2.3), the radiant rate of heat transfer across the plasma/liquid interface is:

$$(H - H_0) \left(\frac{dm}{dt} \right) = (2\pi R_p b) (a_R \sigma T^4) \quad (2.4)$$

where R_p is the plasma radius (m), b is gap distance (m), a_R is non-black body of absorptivity, σ is Stefan-Boltzmann constant ($5.670 \times 10^{-8} \text{ JK}^{-4} \text{ m}^{-2} \text{ s}^{-1}$) and T is temperature (K).

The flow of dielectric liquid due to pressure difference is quantified by continuity and momentum equation. The solution of the equation gives the relationship between the radius of plasma and time.

$$\left(\frac{dR_p}{dt}\right)^2 \left(\ln \frac{R_f}{R_p} + \frac{1}{2} \left(\frac{R_p^2}{R_f^2} - 1 \right) \right) + R_p \left(\ln \frac{R_f}{R_p} \right) \left(\frac{d^2 R_p}{dt^2} \right) = \left(\frac{P - P_o}{\rho_o} \right) \quad (2.5)$$

where, R_f is outer radius of dielectric in the gap (m), P is pressure (bar), P_o is ambient pressure (bar), and ρ_o is specific density of the dielectric (kg/m^3).

In order to accommodate the changing of plasma state with time and the heats of disassociation and ionization, Eubank et al. [67] provide the following state equation:

$$P = \frac{\lambda T \rho}{216.70} \quad (2.6)$$

where, λ is the average number of particles dissociated out of the dielectric molecule.

2. Kinetics approach

In this approach, the plasma formation and its interaction with the electrodes were defined by analyzing the distribution of ions, electrons and neutral particles while the heat input is assumed to be constant. Singh and Ghosh [68] reported that during the plasma formation, the voltage difference between the electrode and the workpiece created a very thin sheath near the cathode, so called plasma sheath. The sheath has a charge imbalance and can sustain a potential gradient, allowing almost the entire potential drop between the electrodes to take place at the sheath region (see Fig. 2.10).

Fig. 2.10 Voltage between electrodes in EDM process [68]

Due to the large potential drop in the sheath region, there is a very strong electric field at the cathode. The negative charge on the surface pulled outwards by the field, causing material removal due to a stress on the surface and inside the electrode.

Most of the potential drop occurs at the plasma sheath. However, there is a small potential drop in the plasma region and a small pre-sheath electric field extends into the plasma which accelerates the ions as they drift towards the cathode. The potential distribution inside the sheath is given by Singh and Ghosh [68] as:

$$\phi(M) = -\left(\frac{\sigma T_e}{e}\right) \ln(1 + M^2) \quad (2.7)$$

where, T_e is electron temperature (constant throughout the whole discharge region), e is the electron charge (1.6×10^{-19} Coulomb), and M is Mach number.

The electrical field, $E(x)$, at the anode or cathode was given as:

$$E^2(x) = \frac{4}{\epsilon_0} n_{se} e \sqrt{\phi_0 \phi_w} \quad (2.8)$$

where, ϵ_0 is permittivity (F/m) and n_{se} is ion density (m^{-3}).

The differences between the two approaches are summarized in Table 2.4.

Table 2.4 The comparison between fluid dynamic and kinetic approaches.

Fluid dynamic approach	Kinetic approach
- Deals with the change in properties of bulk plasma	- Deals with the distribution of various species within the plasma
- Account for the expansion of plasma and use it as the boundary condition for anode and cathode erosion.	- The plasma is quasi-neutral and the electron and ionic distribution in this plasma follows Boltzmann distribution
- Contribution of particles/ions/electrons bombardment in heat transfer equations is neglected.	- Contribution of particles/ions/electrons bombardment in heat transfer equations is essential as the energy source.
- The heat is not constant; it depends on the expansion of plasma	- The heat is assumed to be constant
- Complexities due to unsteady expansion of plasma	- Non complexities from the expansion of plasma because it assumed to be quasi-neutral.
- Flow of liquid dielectric is essential	- Flow of liquid dielectric is not essential

2.3.2.2 Cathode Erosion Modeling

The cathode erosion models were developed to estimate the volume of material removed from the cathode surface during EDM process. The theory used to develop this model can be classified into:

1. Electro-thermal Theory

This is the best supported theory by the experimental evidence. It suggests that the material removal mechanism occurs as a result of an extremely high temperature due to the high intensity of current flowing through the plasma channel. The characteristics of the existing models based on this theory can be summarized as follows (see Appendix A for a complete description):

Table 2.5 Analytical models based on electro-thermal theory

Author(s)	Basic features
R. Snoeys and F. Van Dijck [65]	<ul style="list-style-type: none">• Semi-infinite cylinder• Except for the surface subjected to heat flux, the other surfaces are insulated• No heat transfer to liquid dielectric• Temperature distribution: $T(r, z, t) = T_0 + \sum_{n=1}^{\infty} \frac{c_n}{2\lambda_n} J_0(\lambda_n r) \left\{ e^{\lambda_n z} \left[\operatorname{erf} \left(\lambda_n \sqrt{\alpha' t} + \frac{z}{2\sqrt{\alpha' t}} \right) - 1 \right] + e^{-\lambda_n z} \left[\operatorname{erf} \left(\lambda_n \sqrt{\alpha' t} - \frac{z}{2\sqrt{\alpha' t}} \right) + 1 \right] \right\} \quad (2.9)$
F.S Van Dijck and W.L. Dutre [64]	<ul style="list-style-type: none">• Finite or semi-infinite in z direction• Two dimensional heat flow• The upper electrode surface outside the electrode is insulated• In the radial direction, the medium is bounded by cylindrical surface• The electrode dimension was taken to be about twenty times the heat source diameter• Temperature distribution: $T(r, z, t) = T_0 + \frac{q \cdot r_c}{K_t} \sum_{n=1}^{\infty} a_n J_0(\lambda_n r) \{ \sinh(\lambda_n z) + \sum_{m=1}^{\infty} c_{mn} \sin(\mu_m z) \exp[-\alpha'(\lambda_n^2 + \mu_m^2)t] \} \quad (2.10)$
James V. Beck [69, 70]	<ul style="list-style-type: none">• Semi-infinite cylinder• Disk heat source• Surfaces beyond the disk region are insulated• Constant thermal properties• Constant heat flux• Temperature distribution:

	$T(r,z,t) = T_i + \frac{2qr_c}{K_t} \left\{ \frac{r_c B(z,t)}{r_o^2} + \sum_{i=1}^{\infty} \frac{C_i(z,t) J_0(\lambda_i r) J_1(\lambda_i r_c)}{2[\lambda_i r_c J_0(\lambda_i r_c)]^2} \right\} \quad (2.11)$
S. Tariq Jilani and P.C. Pandey [48, 71, 72]	<ul style="list-style-type: none">• Uniform heat flux with constant radius• Constant thermal properties• The erosion take place at the melting area of the electrode• Temperature distribution: $T(r,z,t) = \frac{q.r_c^2}{K_t} \sqrt{\frac{\alpha'}{\pi}} \int_0^t \exp \left[-\frac{r^2}{4\alpha' t + r_c^2} - \frac{z^2}{4\alpha' t} \right] \frac{1}{(4\alpha' t + r_c^2) \sqrt{t}} dt \quad (2.12)$
Dibitonto et al. [28, 67]	<ul style="list-style-type: none">• Point heat source model for cathode• Fraction of energy for anode, cathode and the plasma are assumed to be constant• Average thermophysical properties of the material apply over the whole temperature range• Temperature distribution: $T(r,z,t) = T_0 + \frac{q.r}{K_t} \operatorname{erfc} \left(\frac{r}{2\sqrt{\alpha t}} \right) \quad (2.13)$

The abovementioned models are considered to be the representatives models since the other published models, such as Carslaw and Jaeger [73]; Erden and Kaftanoglu [74]; Lhiaubet and Meyer [75]; Das, Klotz, and Klocke [76]; and Dhanik and Joshi [77]; are having close similarities in nature with one of them. For instance, the boundary conditions or the heat source used in the model development are similar, resulting in similar solution for the temperature distribution equation.

A stochastic methodology called Data Dependent System (DSS) can also be used to develop the analytical description of the temperature distribution in the EDM process. The approach in this direction has been reported by Pandit and Rajurkar [78].

2. Electro-mechanical Theory

In this theory, the thermal effect is neglected and the material removal mechanism occurs due to a high concentrated electrical field. This is because it is assumed that

the metal does not get enough time to get adequately heated. The electrical field separates the material particles of the electrodes when the cohesion forces in the lattice of the material are exceeded.

Singh and Ghosh [68] reported that the spark radius in this approach is increasing uniformly with time. The electrical field, as given by equation (2.8), is assumed to be steady. The material removal will take place at the surface of the cathode due to the surface stress. The depth of the craters was given by Singh and Ghosh [68] as:

$$z = \left(\frac{3I\sqrt{2m_i(-\phi_w/e)}}{\pi S_y(0,z,t_d)} \right)^{1/2} \tag{2.14}$$

where, I is the net current (A), m_i is the mass of particle (kg), S_y is the yield strength of the anode material (MPa), and t_d is the pulse-on-time.

The comparison between the electro-thermal theory and the electro-mechanical theory is summarized in Table 2.6.

Table 2.6 Comparison between electro-thermal and electro-mechanical theory

Electro-thermal mechanism	Electro-mechanical mechanism
Considers superheating of electrodes due to heat transfer from plasma	Considers strong electrostatic force acting on electrodes
“Melting and superheating” is the main mechanism of electrode erosion	“yielding” is the main mechanism of erosion
Material removal happen at the end of pulse-on-time with some material removal during pulse-on-time	Material yields during pulse on time and is ejected due to electrostatic force
This mechanism give reasonably good results for large pulse-on-time	Predict reasonably accurate MRR values for short pulse-on-time

2.3.2.3 Anode Erosion Modeling

Anode erosion modeling is used to estimate the volume of material removed from the anode during EDM process. All literature on EDM models based on the cathode erosion was also implemented for anode erosion modeling, except for Dibitonto’s model [79] where the anode was treated differently. For single discharge, the crater formed on the

anode was found to be shallower and wider as compared to the cathode. This is due to the collision of electrons with neutral particles in the dielectric, causing the electrons to diffuse and the landing area increases significantly. Therefore, the heat source for anode erosion model is assumed to be an expanding circular heat source [79].

The analytical solution of the temperature distribution for this model is given by Patel et al. [79] as:

$$T(r, z, t, r_g) = \frac{r_g}{2k} \int_0^{\infty} J_0(\lambda r) J_1(\lambda r_g) X \frac{d\lambda}{\lambda} \quad (2.15)$$

where r_g is the disk heat source radius (m), J_0 and J_1 are Bessel functions of zero and first order, and

$$X = e^{-\lambda z} \operatorname{erfc}\left(\frac{z}{2\sqrt{\alpha t}} - \lambda\sqrt{\alpha t}\right) - e^{\lambda z} \operatorname{erfc}\left(\frac{z}{2\sqrt{\alpha t}} + \lambda\sqrt{\alpha t}\right) \quad (2.16)$$

where erfc is an error function.

From hereon, the following review is referenced without author names, a contrast from the above.

2.3.3 Process Monitoring and Control

Most micro-EDM machines are required to provide certain safety and adaptive-control functions to improve productivity. Therefore, real time monitoring and control of the machining process must be established. Fig. 2.11 shows the basic schematic diagram of the process monitoring and control system.

Fig. 2.11 Basic schematic diagram of process monitoring and control for EDM process

2.3.3.1 Pulse Parameter

The real-time monitoring and control is generally based on the identification of the pulse train inside the discharge gap. These pulses, classified as sparking, arcing, and short-circuit; are dependent on the ignition delay time, and have a direct influence on the MRR, TWR, and SR [80]. It was claimed that the recognition and classification of the different pulses provided a viable option of monitoring and controlling the sparking process by measuring the related gap voltage and current.

A neural-network method to establish the relation between tool-workpiece gap signals and the pulse types, as neural network is a highly flexible tool for pattern recognition and classification has been proposed [81]. A feed-forward neural network with the back-propagation learning algorithm is used to construct the monitoring process model. Based on this model, EDM pulse types can be classified quickly and used to control the next process parameter setting. Similarly, an abductive network method of classifying and regulating the EDM pulses for various machining condition was suggested [82]. Fig. 2.12 and Fig. 2.13 show the schematic diagram of EDM pulse monitoring process and the configuration of the neural network respectively.

Fig. 2.12 Schematic diagram for pulse monitoring of EDM process [81]

Fig. 2.13 Configuration of the neural network to classify EDM pulses [81]

The effect of different pulses on MRR and TWR has been studied [83]. It was found that in die-sinking EDM the MRR depends on the discharge duration while the TWR was caused only by undelayed and late ignition discharges. Based on the result, an adaptive optimization of the gap controller was developed to reduce the number of undesirable pulses. On the other hand, a GA-based neural network was used to study the effect of different process parameters on MRR, TWR and SI [84].

2.3.3.2 Time Domain

Rajurkar et al. argued that the gap voltage is not a good indicator of the dynamic responses taking place at the spark gap largely due to the existence of high frequency (HF) noise component on the signal [85]. The authors suggested monitoring the time ratio of transient arc measured by the pulse-on-time, which shows the trend towards undesirable arcing.

Fig. 2.14 EDM original waveform transform results [86]

(a) Voltage, (b) Current, (c) Wavelet voltage coefficient, (d) Wavelet current coefficient, (e) Identity result. (V=120V, I=30 A, f_s =20 kHz)

The time domain of different pulses where the waveform were obtained from the voltage and current between the electrode and the workpiece of the EDM machine and calculated by the wavelet transform has been studied by Yu et al. [86]. The wavelet transform is a tool to handle transient non-stable signals. It was claimed that after the transformation, the machining condition can be classified easily and used for the on-line process monitoring and control. The illustration on the original waveform transform results using this method is given in Fig. 2.14.

A monitoring and adaptive integral control for EDM by measuring the various transient pulses and regulating the cycle time of the periodical retraction (jumping) of the electrode according to the gap condition has been reported [87]. The experimental results showed that the proposed system results in higher MRR, better machining stability, and complete avoidance of arc damage. A self-tuning regulator for an EDM servo control system, which directly adjusts the servo feed rate based on the ratio between the discharge time and the off time from the gap has been reported [88].

2.3.3.3 Fuzzy Logic

The application of fuzzy set theory to the adaptive control system in EDM has been reported by Lin et al. [23, 25]. The measurement results of EDM gap voltage and gap current were classified by using a machine learning method and used for the control purposes. Several authors claimed that the fuzzy logic control implements a control strategy that is adopted by a skilled operator to maintain the desired machining process [89]. However, the definition of membership functions for each fuzzy set is not straightforward and is based on exploratory means to classify various discharge pulses.

A fuzzy pulse discriminator established on the linguistic rules acquired from the knowledge of experts and expressed mathematically through the theory of fuzzy sets has been suggested [90]. A machine learning method based on a simulated annealing algorithm is used to automatically synthesize the required membership functions. Fig. 2.15 (a) illustrates the basic configuration of a fuzzy EDM machine. The discharge signals are fuzzified by the membership functions provided by the knowledge base of the machine. Then, the decision making logic conducts fuzzy reasoning of the linguistic rules extracted from the knowledge base so that the pulse can be classified and an appropriate control action will be generated to optimize the EDM process. The schematic diagram of the fuzzy pulse generator can be seen in Fig. 2.15 (b).

Fig. 2.15 Fuzzy EDM machine [90]

Recently, Tarng and Jang [91] used genetic algorithms (Gas) to synthesize the required membership functions automatically. In addition, a fuzzy logic monitoring to control the jump heights and the approaching movement of the tool electrode according to the calculated stability was used [92].

2.3.3.4 Radio Frequency

The research work at the University of Birmingham revealed that during EDM process, an intense Radio Frequency (RF) signal is emitted due to the high rate of current change [93-95]. The intensity of this signal was found to drop rapidly as arcing is about to take place. An antenna coupled with a RF amplifier was used to monitor this signal and detects any drop in the intensity of signals to a threshold value whenever the discharge changes from sparking to arcing.

The evaluation of the effectiveness of RF control and the use of orbital motion in reducing the surface damage of EDM machined features has been reported [96]. It was found that at pulse-on-time less than 100 μ s, MRR is higher and the corresponding surface roughness is lower when RF control unit is applied. At larger pulse-on-time, MRR is lower but the surface is smoother with RF control. Fig. 2.16 shows the schematic diagram of EDM machine with RF control.

Fig. 2.16 Schematic diagram of EDM machine with RF monitoring and orbital motion control [96]

2.3.4 Tool Wear Compensation

In micro-EDM process, electrode wear causes a geometrical error in the machined profile. Fig. 2.17 illustrates the shape change on a cylindrical electrode used in micro-EDM. The problem arises in fabricating blind holes because the wear will reduce the electrode length. As a result, the real depth of the holes will be smaller. For micro-EDM milling, a rotating cylindrical tool electrode follows a programmed path to create the cavity on the workpiece. The wear on the electrode will create an error in the produced depth. The shape of the electrode also becomes hemispherical, which causes errors in the shape of the parts. Therefore, a method to compensate the electrode wear is highly necessary to ensure the geometrical accuracy of finished products.

Fig. 2.17 Types of electrode wear in EDM [97]

2.3.4.1 Z level compensation

In this method, the machining process was done by compensating the tool wear continuously or in a small increment along the tool path. In order to compensate the wear on the electrode, the electrode was fed downwards after it moved a certain distance [98]. The drawbacks of this method are:

- 1. it requires an accurate wear estimation and
- 2. it does not work well in fabricating 3D cavity.

2.3.4.2 Uniform Wear Method (UWM)

The basic principle of this method is that under certain condition, the shape of the electrode is recovered due to the tool wear after each layer machining [99]. Thus, the electrode may become shorter, but the shape is kept constant. It was assumed that the wear will only occur on the bottom surface of the electrode. Very accurate estimation on the wear amount is required, because an error on the estimation would cause accumulated effect through the layer. Fig. 2.18 shows the different between the wear in common EDM and EDM with UWM method. The machining results using UWM are depicted in Fig. 2.19

Fig. 2.18 Electrode tool wear [98]

(a) 1/8 sphere in a square cavity (b) Circular cavity with a cone at the center

Fig. 2.19 UWM machining results [98]

The tool path was specially designed to ensure that the electrode shape is restored after machining of each layer [100]. This is done by using an overlapping tool paths and a very small layer thickness. The tool paths were designed from the values of the cross section of the electrode, the area of the layer surface, the depth of cut and the volumetric wear ratio which are assumed to be constant [101]. It was found that the accuracy of the machined profile is within 1 μm for micro-EDM and 0.14 mm for conventional EDM [98].

The drawbacks of this method are:

1. it requires an accurate model to estimate the tool wear,
2. an error will be accumulated through each layer,
3. side wear is not negligible and will introduce error in the machined profile, and
4. it requires an accurate tool path to ensure that the electrode is always restored after machining of each layer.

2.3.4.3 Multi-electrode

The machining process will always contain an error on the geometrical accuracy of the products. Therefore, the processes were repeated a number of times with a new or reground micro-electrode until the required shape are obtained. A simple method to machine a number of different milling paths, each covering the complete volume of the cavity required was reported [2]. For each path, the Z-coordinate was restarted by using the first contact of the electrode and the workpiece as zero reference. By using this approach, the amount of wear from the previous path can be estimated and used to indicate whether the machining can be continued or the electrode need to be redressed first. The machining process is continued until no more wear detected from the electrode. An illustration of the multi-electrode method is given in Fig. 2.20.

Fig. 2.20 tool wear compensation using multi-electrode method [2]

The drawbacks of this method are:

1. it is time consuming and
2. the number of electrodes required are difficult to predict.

2.3.4.4 On-line wear monitoring system

An on-line tool wear measuring system by using an automatic touch-sensing mechanism has been introduced [102]. The measurement was taken periodically during the process by taking the electrode to the touch-sensing device and the results were used to compensate the tool path. Fig. 2.21 shows the schematic diagram of the system.

Fig. 2.21 The schematic diagram of automatic touch-sensing EDM process [102]

On the other hand, an on-line monitoring system to detect the electrode wear by a laser range sensor with a resolution of 0.1 μm and an available length of the detector ray of 65 mm has been proposed [103]. Fig. 2.22 shows the measurement method where the distance of the detector array not to receive the laser beam corresponds to the shape of the electrode. The measurement results are then used to define the redressing requirements for the electrode, which was done on the machine.

(a) Schematic diagram of on-line measurement method

(b) A set-up of on-machine dressing facility

On-machine dressing process

Fig. 2.22 On-line measurement of tool wear by laser a laser range sensor [103]

Recently, a real-time wear sensing for tool wear determination and improved wear compensation in layer-by-layer machining was introduced [104, 105]. The discharge pulse was analyzed and the numbers of effective (normal) discharges were used to indirectly determine the volumetric tool wear. This volumetric tool wear result is then used as an input to estimate the tool wear compensation required in the machining process.

The drawbacks of this method are:

1. time consuming and
2. expensive.

2.4 Outcome of the Literature Review

The major outcomes of the literature review which has direct effects on this research work are as follow:

1. The material removal mechanism in EDM process is very complex and stochastic in nature. As a result, it is very difficult to understand and predict the process analytically. However, in order to fully utilize the process, a better understanding on the material removal mechanism and a reliable analytical model are highly necessary. Therefore, an analytical model is required to correlate the process parameter with the process performances. These issues are discussed in Chapter 4.
2. Process parameters affect the process performance of micro-EDM process. An understanding of the relationships between the process parameter and the process performance to achieve an optimum machining process is vital. It is also crucial for on-line control system, as the system works by adjusting the process parameters to achieve a better process performance. An attempt to address this issue is given in Chapter 4.
3. In micro-EDM, the requirements of accuracy in the machined feature are more demanding since minute imperfections are magnified in the micro scale. Furthermore, the occurrences of tool wear which lead to a lack of machining accuracy in the geometry of the workpiece has become the major setback for this process. Therefore, to improve MRR and reduce the influence of tool wear, an online monitoring and control system capable of directly retrieving the information

of the process from the discharge gap and utilized the data to control the process have to be developed. Attempts to address this problem are discussed in Chapter 5.

4. The wear on the electrode will create an error in the produced depth and in the shape of the micro-EDM machine profiles. Therefore, a method to compensate the electrode wear is highly necessary to ensure the geometrical accuracy of finished products. Contributions made in this issue are described in Chapter 5.

CHAPTER 3

APPROACH TO IN SITU MONITORING AND EXPERIMENTAL METHODOLOGY

This chapter provides an overview of the approach to in situ monitoring of the micro-EDM process, experimental methodology, procedures, and equipment used for the research work. In the first section, the method to accomplish the objectives is described. The second section explains the experimental set up and procedures. The third section deals with the instrumentation to characterize the experimental results. Finally, the last section will give a summary on the experimental method.

3.1 Approach to In situ Monitoring of the Micro-EDM Process

It is believed that the micro-EDM process performances can be analytically defined using knowledge of the crater geometry, specifically the crater diameter and depth. The reason behind this is because the crater geometries are directly related with the volume of the material removed from the electrode and the workpiece; hence they are directly related with the MRR and TWR. In addition, the machined surface is also highly dependent on crater geometry which constitutes the profile, hence the SR. Therefore, a methodology to determine crater geometries is necessary. This is accomplished by developing a theoretical model to predict the crater's diameter and depth using the process parameters, namely material properties, voltage, current, and pulse-on-time.

Thus, in this research work, the first step is to develop a micro-EDM theoretical model to predict the crater geometries based on the process parameter. The proposed model is based on an electro-thermal material removal mechanism (section 4.2). The second step is the validation of the model using single discharge experimental observations (section 4.2.3). For the third step, the micro-EDM predictive model is used as a basis for the development of the MRR, TWR, and SR analytical models (section 5.1). Since the model computation used the voltage and current data, which are captured in real time; this method can be applied as an in situ process monitoring system for micro-EDM process in terms of MRR, TWR and SR. In the last part, the TWR monitoring model is applied in the Z-

compensation technique to show the effectiveness of the developed monitoring technique (section 5.3). The overall steps taken in the research work is depicted in Fig. 3.1.

Fig. 3.1 Research work flowchart

3.2 Experimental Methodology

Experimental works based on single discharge and multiple discharges are performed to acquire a good empirical reference for the analytical model and the process monitoring technique. The results are also used to understand the relationships between the process parameters and the process performance of micro-EDM process. The experiments are conducted using AISI 4140 alloy steel and Titanium (Ti-6Al-4V) as the workpiece materials with dimensions of 10 mm x 10 mm x 10 mm. AISI 4140 is used since the comparison of previous EDM models were conducted based on the experimental results of steel from Dibitonto [28]. Hence, the results of this research work can be compared with those previous models. As for Titanium, this material is used due to its high strength-to-weight ratio which makes it difficult for conventional machining. As the electrode material, pure tungsten rod with the diameter of 125 μm and 300 μm are used. The properties of the workpiece and electrode materials are given in Table 3.1.

Table 3.1 Physical properties of AISI 4140 alloy steel and Tungsten [106]

Properties	AISI 4140	Ti-6Al-4V	Tungsten
Average density [kg/m ³]	7600	4506	19300
Average thermal conductivity [W/m.K]	38.95	21.9	130.2
Average specific heat [J/kg.K]	473	523.5	141.3
Melting temperature [K]	1688	1941	3387
Hardness [Rockwell C]	22	36	35

3.2.1 Experimental Rig

3.2.1.1 Single discharge experimental rig

The experimental rig as shown in Fig. 3.2 consists of a 3-axis linear stage for motion control, electrode and workpiece holder, dielectric tank, RC circuit generator, and data acquisition system. The linear stage is driven by Newport 850G-LS linear actuator which has 0.007985 μm encoder resolution, 50 mm travel distance and a cumulative accuracy of <0.1% of travel. The motion controller Newport™ ESP6000 is used.

Fig. 3.2 Single discharge experimental set up

In Fig. 3.3, the schematic diagram of the RC circuit developed as the pulse generator and the data acquisition system is illustrated. The circuit is built with different combination of capacitor values in order to provide varied energy input for the experiments, ranging from 2.5 μJ to 50 mJ. The objective of this circuit is to deliver a predetermined amount of energy to the discharge gap for the single discharge experiments. Additional circuit using 1.5 Volts DC power supply is added to the system for the gap distance setting.

Fig. 3.3 Schematic diagram of the experimental circuit and data acquisition system

During the discharge, the voltage and current between the electrode and the workpiece are captured using the Tektronix™ P5205 voltage probe and Tektronix™ CT-1 current probe. The data waveform is stored using an oscilloscope for further data processing.

3.2.1.2 Multiple discharge experimental rig

The multiple discharge experiments are conducted to develop the process monitoring technique of micro-EDM process in terms of MRR, TWR, and SR. The set up is realized using a commercially available micro-EDM system, MG-E72W™, as the platform. The experimental set up used in this work is shown in Fig. 3.4.

Fig. 3.4 Multiple discharges experimental set up

3.2.2 Experimental Procedure

3.2.2.1 Single discharge experimental procedure

The experimental works are accomplished by mounting the electrode onto the linear stage to control its position relative to the workpiece. For the gap distance zero settings, the electrode and the workpiece are connected to a 1.5 Volts DC power supply. The electrode is slowly traversed ($0.05 \mu\text{m}/\text{sec}$) to the workpiece until a short-circuit occurs. The short-circuit condition can be recognized by using the oscilloscope to observe the time when the current in the inter-electrode gap started to flow. At this point, the position is taken as the zero gap distance.

The machining processes are accomplished by changing the switch B connection at the electrode to the RC circuit (see Fig. 3.3). The electrode is moved upwards according to the gap distance requirement and upon reaching the required distance, the discharge energy is

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Approach to In situ Monitoring and Experimental Methodology

released to create a micro crater. The machining parameters used in this process are shown in Table 3.2.

Table 3.2 Machining parameters for single discharge experiments

Workpiece	:	AISI 4140 alloy steel
Electrode	:	Tungsten rod
Dielectric fluid	:	Synthetic electric spark oil (Daphne Cut HL-25)
Power supply voltage	:	100 Volts
Energy input	:	5 μ J, 25 μ J, 50 μ J, 75 μ J, 100 μ J, 125 μ J, and 150 μ J
Polarity	:	Positive and negative

The voltage and current between the electrode and the workpiece are captured and stored in the oscilloscope during the discharge. The measurement of the diameter and depth of the crater are performed by using WYKO NT2000. Scanning Electron Microscopy is utilized to analyze the appearance of each crater.

3.2.2.2 Multiple discharge experimental procedure

The development of process monitoring technique for micro-EDM consists of two parts of experimental work. The first part deals with the MRR and TWR while the second part concerns the SR.

The development of process monitoring technique for the MRR and the TWR are based on the volume removed at both the workpiece and the electrode during the machining process. The volumes are determined by measuring the tool electrode and the machined hole profiles. The hole profiles can be inspected by cross-sectioning every specimen. However, there are practical difficulties using this method due to the small feature sizes of 300 μ m. Therefore, to simplify the workpiece profiles measurement, the specimen is initially cut into two half portions. In order to provide a smooth and flat mating surface, the two cut surfaces are subjected to grinding followed by polishing. The two halves are butt together in contact and finally mounted on the X-Y table of a micro-EDM machine.

The tool electrode is machined using Wire Electrical Discharge Grinding (WEDG) to a diameter of 300 μ m with a flat bottom surface. The center of the electrode is positioned to the parting line of the workpiece at the onset of the experimental work. During each experimental run, the voltage and current on the discharge gap are measured and captured using the oscilloscope. The machining time is also taken at the end of the experiment. The electrode and workpiece hole profiles are then measured to obtain the volume removed.

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The process is repeated five times for each parameter setting to ensure the reliability of the data. Table 3.3 shows the process parameters used in the experiments.

Table 3.3 Machining parameters for the MRR and TWR investigation

Workpiece	:	AISI 4140 alloy steel
Electrode	:	Tungsten
Dielectric fluid	:	Synthetic electric spark oil (Daphne Cut HL-25)
Power supply voltage	:	110 Volts
Capacitor	:	3300 pF
Polarity (to the workpiece)	:	Positive
Depth setting	:	250 μm , 500 μm , 750 μm and 1000 μm

As for the SR experiments, the workpiece specimen is initially polished and then mounted on the micro-EDM machine. The machine setting is varied for each experimental run which is repeated five times to ensure the reliability of the data. The programmed depth of each hole is set at 100 μm for the collection of surface measurement data taken at bottom surface of the machined holes. The tool electrode is machined using Wire Electrical Discharge Grinding (WEDG) to a diameter of 300 μm with a flat end.

At the end of each experiment, the workpiece is cleaned using solution in an ultrasonic cleaner. The measurement of surface roughness is made using a confocal profiler set at a cut-off length of 0.25 mm. Table 3.4 shows the process parameters used in the experimental work.

Table 3.4 Machining parameters for the surface roughness investigation

Workpiece	:	AISI 4140 alloy steel and Ti-6Al-4V
Electrode	:	Pure tungsten
Dielectric fluid	:	Synthetic electric spark oil (Daphne Cut HL-25)
Power supply voltage	:	80 V, 90 V, 100 V and 110 V
Capacitor	:	3300 pF
Polarity (to the workpiece)	:	Positive
Hole depth setting	:	100 μm

3.3 Characterization Techniques

Characterization techniques are the measurement and inspection methods used to analyze relevant features quantitatively or qualitatively. In this section, the equipment used to analyze the experimental results are discussed briefly.

3.3.1 Voltage and Current Measurement

During the experimental runs, the voltage and current from the discharge gap are required for the observation of discharge mechanism and for the calculation of energy used in the process. Therefore, the measurement of voltage waveform and current waveform is highly crucial to achieve the objectives of this research work. The voltage and current probes used are shown in Fig. 3.5.

Fig. 3.5 Voltage and current probes

3.3.2 Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) is used to visualize the characteristics of the craters from the single discharge experiments and the surface appearance of the multiple discharge experiments. The SEM machine used in the experiments is depicted in Fig. 3.6.

Fig. 3.6 SEM machines used for surface characterization

3.3.3 Dimensional and Geometrical Measurement

In the present work, the dimensional and geometrical measurements are done using three types of characterization equipment, namely WYKO NT2000, Confocal Imaging Profiler, and ROI OMIS II Optical Microscope.

WYKO NT2000 is used to analyze the micro crater created from a single discharge experiment (see Fig. 3.7). This machine is capable of measuring surface heights from 0.1 nm to several millimeters with a roughness measurement resolution of less than 1 Å.

Fig. 3.7 WYKO™ NT2000

ROI OMIS II Optical Microscope which has 203.2 mm measurement range, 0.001016 mm resolution, and 0.004064 mm per 25.4 mm accuracy is used to measure the dimension of the tool and workpiece before and after machining. The measurement of surface roughness is made using the PLμ confocal imaging profiler (SensoFar) which uses white light interferometry and a scanning device to achieve a confocal image. The resolution of this device is 0.2 μm while the measurement ranges are 95 μm for 20x magnification lens and 38.4 μm for 50x and 100x lenses.

Fig. 3.8 ROI OMIS II™ Optical Microscope

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Fig. 3.9 PL μ ™ Confocal Imaging Profiler

3.4 Summary

The approach in the development of in-situ monitoring of the micro-EDM process and the experimental methodology used in the research work are described in this chapter. In addition, the equipments used to characterize the experimental results are described. The following chapter will provide the development of an analytical model to estimate the volume of material removed from the workpiece surface.

CHAPTER 4

ELECTRO-THERMAL MODELLING OF MICRO-EDM PROCESS

This chapter presents the development of the theoretical micro-EDM model. The first section provides an evaluation on existing analytical models by means of a comparison with the experimental data. The objective of this section is to elucidate the characteristics of each model and to identify the appropriate model which provides the closest approximation in relation to the real process. The second section deals with the development of the theoretical micro-EDM model.

4.1 Evaluation on Existing Analytical Model

The evaluation on the existing EDM models is focused to the electro-thermal models since it is believed to be more prevalent for large pulse-on-time ($>5 \mu\text{s}$) while the electro-mechanical model is more prevalent for short pulse-on-time ($< 5 \mu\text{s}$) [68]. Five models, namely Snoeys and Van Dijck's model [65], Van Dijck and Dutre's model [64], Beck's model [69], Jilani and Pandey's model [48, 71, 72], and Dibitonto, Eubank, Patel, and Barrufet's model [28]; are studied in terms of the temperature distribution, crater dimensional geometry, and MRR at the cathode.

The temperature distributions of the models are calculated numerically according to the equations given in the literature (section 2.3.2.2). The main input used in the calculations are discharge voltage (V), discharge current (I), pulse-on-time (t_d), material properties, and any specific assumptions used in the model development (i.e. radius of heat flux). In several cases, the model equations are given in a series form where the calculations are done using 100 terms in order to achieve reasonable accuracy and computation time.

The models from Snoeys [65], Van Dijck [64], and Beck [69]; are all based on a disk heat source with a certain radius of heat flux. However, information or guidelines to determine the radius of heat flux for Snoeys's and Van Dijck's models are only available for 100 W power input [64, 65]. Guidelines to determine the radius is not available for Beck's model.

Therefore, in order to present an objective comparison, the same equation used in Jilani’s model, Equation (15), is used to approximate the heat flux radius.

In the Snoey’s, Van Dijk’s, and Beck’s models, the outer radius of the insulated surfaces must be defined in the calculation. In the analysis, the outer radius is assumed to be [107]:

$$r_o = 50.r_c \tag{4.1}$$

where r_o is the outer radius of the insulated surface [μm] and r_c is the radius of the heat flux [μm].

4.1.1 Experimental data

The process parameters used in the analyses are taken from the available experimental data given by AGIE Corporation, as reported by Dibitonto et al [28]. The data were obtained from a diesinker EDM machine with steel as the workpiece and copper as the electrode. These data are chosen because the process parameters and material properties used are given in details. In addition, the data were taken from an independent and established machine tool manufacturer in EDM to ensure its reliability. The experimental data for a discharge voltage V of 25 Volts are tabulated in Table 4.1.

Table 4.1 Experimental data (discharge voltage = 25 V) [28]

Current (I) [A]	Pulse-on-time (t_d) [μs]	Pulse-off-time (t_{off}) [μs]	Material removal rate (MRR) [mm^3/min]	Crater radius (r_{crater}) [μm]
68	560	10	559	85
58	420	7.5	346	67
44	240	5.6	246	60
36	180	4.2	226	60
25	100	4.2	125	48
20	56	3.2	89.7	38
12.8	42	3.2	50.5	30
10	32	2.4	32.0	27
8.5	24	2.4	23.2	24
5.3	18	2.4	8.4	15
3.67	13	2.4	3.1	13
2.85	7.5	1.3	1.6	10
2.34	5.6	1.0	0.3	8

4.1.2 Temperature distribution

The calculation results of the temperature distribution of the five models ($V=25\text{ V}$, $I=12.8\text{ A}$, $t_d=42\text{ }\mu\text{s}$, material=AISI 4140, number of terms=1000) are depicted in Fig. 4.1 (refer to Appendix A for the equations used). This point is used in the calculation since it was used

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as the central data point to acquire the fraction of power constant going to the cathode in Dibitonto’s report [28].

Fig. 4.1Temperature distributions of the cathode surface

V=25 V, I=12.8 A, t_d =42 μ s, material=AISI 4140, number of terms=1000

The illustrations show that the temperature profiles and isotherm surfaces, which are shown by the differences in shaded color and lines, vary for each model. Snoeys’s model has a bowl shape with a nearly flat bottom surfaces (see Fig. 4.1(a)). In Fig. 4.1(b), Van Dijk’s model provides similar characteristics with larger affected distance for the same

temperature, i.e. 2000 K is shown at approximately 2 times further as compared to Snoeys's model in X-axis direction. Beck's model shown in Fig. 4.1(c) gives almost similar results with Snoeys's model. Jilani's model provides more crescent-like shape with gradual change of temperature in X and Z directions (see Fig. 4.1(d)). On the other hand, Dibitonto's model as shown in Fig. 4.1(e) gives semi circular isotherm surfaces, as expected from using a point heat source model.

4.1.3 Dimensional geometry of crater and erosion rate

The analyses of the material removal were based upon the assumption that the amount of the molten material at the end of the pulse-on-time is completely removed by the shockwave generated in the dielectric. Therefore, the boundary of resulted crater was taken from the isotherm surface of the melting temperature of the material under consideration.

Fig. 4.2 illustrates the differences on the crater profile obtained for each model. Snoeys's model shows a bowl shape crater with a nearly flat bottom surface. Similar shape is also shown by Beck's model, but with approximately 20% larger size in terms of the crater diameter and depth. Jilani's model shows a crescent-like shape with parabolic edges until the center of the crater while Van Dijck's model yields large crater diameter and depth with a nearly hemi-spherical shape. As for Dibitonto's model, a perfect hemi-spherical crater shape resulted. These variations are thought to be due to the use of a disk and point heat source approximation. A disk heat source distribute the heat flux in a circular area, creating a large ratio of the diameter to depth, i.e. at 25 V, 12.8 A, and 42 μ s pulse-on-time, the ratios are 9.4, 2.3, 7.9, and 8.7 for Snoeys's, Van Dijck's, Beck's, and Jilani's models respectively. In contrast, a point heat source transfers the heat uniformly in radial direction, resulting in a hemi-spherical shape; and thus the ratio is 2.

Fig. 4.2 Crater geometry ($V=25$ V, $I=12.8$ A, $t_d=42$ μ s, material=AISI 4140)

The comparison results between the theoretical and experimental data in terms of diameter and MRR are depicted in Fig. 4.3.

Fig. 4.3 Comparison between the experimental and theoretical results

In general, the crater's diameter and MRR trend for each model with increasing discharge energy is almost comparable. An exceptional large value is shown by Van Dijck's model where it is shown that the MRR approximation is far above the experimental data. The maximum ratios between the theoretical and experimental values for this model are 6.1 at 609 mJ and 1399 at 0.33 mJ for the diameter and MRR respectively. Snoeys's model yields very close results with Beck's model, where the ratio with the experimental results lies in the range of 2.3 to 4.67 and 3.9 to 203 for the diameter and MRR respectively. The results of Jilani's model show a closer approximation with 1.6 to 3.9 diameter ratio and 1.9 to 45.8

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MRR ratios. Dibitonto’s model shows the closest agreement with the experimental plot as compared to the other models, especially for large discharge energies (>1.2 mJ). This model gives a diameter ratio of 1 to 1.9 and MRR ratio of 1.2 to 46. The overall ratio of each model in terms of the diameter and MRR is illustrated in Fig. 4.4.

Fig. 4.4 Ratio between numerical and experimental data

Based on the comparative analyses, Dibitonto’s model is able to predict the dimensional geometry and erosion rate of the process with good accuracy, especially for large discharge energy (>1.2 mJ). The other models tend to overestimate the temperature distribution of the workpiece, resulting in larger crater geometry and erosion rate. This is thought to be due to the use of different fraction of energy for Dibitonto’s model ($F_c=18\%$) whereas the

other models assumed that half of the discharge energy is consumed during material removal ($F_c=50\%$). In addition, the error might also introduced by the approximation error of the heat flux radius which has a high influence on the numerical results for the first four models.

A simple trial of using 18% of energy fraction to the cathode and different heat flux approximation is conducted for Snoeys and Van Dijck’s model [65], Van Dijck and Dutre’s model [64], Beck’s model [69], and Jilani and Pandey’s model [48, 71, 72] to verify the effects of those parameters. The radius of heat flux approximation used is given as [79]:

$$r_g = 0.778 t_d^{3/4}$$

(4.2)

The outcomes at the condition for 25 Volts, 12.8 Amperes, and 42 μ s pulse-on-time, show that the approximation results are greatly enhanced. The ratios between the theoretical and experimental results are illustrated in Fig. 4.5. In terms of the diameter and MRR, Snoey’s model yields the best approximation with 1.08 and 1.9 ratios, followed by Jilani’s model with 1.1 and 2.0 ratios. This evidence clearly shows that the disk heat source model can be improved further by improving the approximation of the heat flux and energy fraction.

Fig. 4.5 Ratio between the theoretical and experimental data (diameter and MRR)
($V=25$ V, $I=12.8$ A, $t_d=42$ μ s, material=AISI 4140)

Based on the presented results, Dabitonto’s model is shown to be the most appropriate model to provide the initial approximation of the conventional EDM process. The simplicity of its equation provides a fast processing time with adequate accuracy.

However, it should be noted that in terms of the crater shape, due to the simplification by using a point heat source, the crater shape is hemispherical instead of having a bowl shape with a shallow bottom surface. Higher accuracy can be introduced by using the heat disk source model with a trade off in longer processing time (i.e. Snoey's model calculation time take approximately 20 times longer as compared to Dibitonto's model computation time).

4.2 Micro-EDM Analytical Model Development

Based on the existing models evaluation, the approximation of the crater's diameter and MRR values have large discrepancy at low discharge energy as compared to the results at higher discharge energy. Therefore, the application of these models in micro-EDM where the discharge energy and the pulse-on-time are generally less than 500 W and 5 μ s respectively; will lead to erroneous approximation of the crater geometries and material removal. The difference between conventional EDM and Micro-EDM in terms of discharge energy level makes a direct application of the models to the latter process inaccurate. Another important result from the evaluation of the existing model is the fact that the use of a disk heat source model is crucial to ensure the accuracy of the model.

Therefore, an analytical model used for micro-EDM process needs to be developed. An attempt in this direction has been reported [77] for the development of plasma channel. However, no attempt has been made for the modelling of the anode and cathode erosion.

In this research work, a two dimensional heat transfer for a material subjected to a disk heat source on its surface is required as the foundation for the micro-EDM model development. There are three important parameters which have to be considered in order to ensure the appropriateness of applying this model since it is adopted from the conventional EDM models. The parameters are the heat flux radius, the fraction of discharge energy going to the anode and cathode, and the portion of the material removed from the molten area.

Empirical equations are established to approximate the boundary conditions for determining the heat flux radius of the anode and cathode. Fig. 4.6 illustrates the schematic diagram of the anode, cathode, and plasma channel in the EDM process.

Fig. 4.6 Schematic diagram of Micro-EDM process

Several simplifying assumptions are used for the model development. The main assumptions are:

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

The main differences between the assumptions used in this work as compared to the assumptions used in the existing models [28, 48, 64, 65, 67, 69-72] are the fraction of energy used for material removal and the fraction of the material removed from the molten area.

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In order to obtain the boundary conditions for the anode and cathode, the equivalent uniform heat flux radius for the anode and cathode are determined empirically using similar machining parameters in single discharge experiments. The energy distribution is considered to be uniform over the heat flux radius. By assuming that the heat flux diameter is close to the crater diameter, the heat flux is determined using the power regression of the experimental data.

Fig. 4.7 Crater diameter versus pulse-on-time (specimen: AISI 4140)

As shown in Fig. 4.7, the experimental data are scattered around the power regression lines, both for the anode and cathode. The variations are largely due to the irregularity of the crater shapes from the single discharge experiment results. Since the data were measured randomly across the craters using WYKO NT2000, the variations are to be expected. Based on the results, the heat flux radius for the anode and cathode for the discharge energy range of 5 μJ to 150 μJ are determined as follows:

$$R_{anode} = 0.0284.t_d^{0.9115} [\mu\text{m}] \quad (4.3)$$

$$R_{cathode} = 0.0425.t_d^{0.8095} [\mu\text{m}] \quad (4.4)$$

where R_{anode} and $R_{cathode}$ are the heat flux radius at anode and cathode respectively, and t_d is the pulse-on-time in nanoseconds. The R-squared value for R_a and R_c are 0.9651 and 0.9301 respectively (see Appendix B).

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It has been shown [28] that the fraction of energy transferred to the anode and cathode are fairly constant. An attempt has also been made [67] to show that superheating is the main mechanism for material removal in EDM. Therefore, it is assumed that the material in the superheated area is removed completely while only a constant fraction of the material in the molten area is removed. To simplify the problem in determining the constants for the energy transferred to the anode and cathode, as well as the fraction of the molten area, a combination of these factors are used instead of treating them independently. Fig. 4.8 illustrates the schematic diagram of the model based on the abovementioned assumptions.

Fig. 4.8 Schematic diagram of the electro thermal model

The governing partial differential equation (PDE) for this heat conduction problem without heat generation is given by:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (4.5)$$

The initial condition gives:

$$T(r, z, 0) = 0 \quad (4.6)$$

And, the boundary conditions are:

$$-K_t \frac{\partial T}{\partial z} = \begin{cases} q & ; \quad 0 < r < R \\ 0 & ; \quad r > R \end{cases} \quad (4.7)$$

$$T(\infty, \infty, t) = 0 \quad (4.8)$$

where K_t is the average thermal conductivity [W/m.K] of the material and α is the thermal diffusivity of the material [m^2/s] which can be written as:

$$\alpha = \frac{K_t}{\rho \cdot C_p} \quad (4.9)$$

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where ρ is the average material density [kg/m^3] and C_p is the average specific heat [J/kg.K].

The solution of the PDE is derived by using the integral transform method and given by [73]:

$$T(r, z, t) = \frac{q.R}{2K_t} \int_0^\infty J_0(\lambda r) J_1(\lambda R) \left[e^{(-\lambda z)} \text{erfc} \left(\frac{z}{2\sqrt{\alpha t_d}} - \lambda \sqrt{\alpha t_d} \right) - e^{(\lambda z)} \text{erfc} \left(\frac{z}{2\sqrt{\alpha t_d}} + \lambda \sqrt{\alpha t_d} \right) \right] \frac{d\lambda}{\lambda} \quad (4.10)$$

where R is the heat flux radius of the anode or cathode [m], J_0 and J_1 are Bessel functions of the first kind of zero and first order respectively, and erfc is the complementary error function.

The heat flux q is given by:

$$q = \frac{C.V_a.I_a}{\pi.R^2} \quad (4.11)$$

where V_a is the average voltage during pulse-on-time [V], I_a is the average current during pulse-on-time [A], and C is the combination of the fraction of energy transferred and fraction of molten area for the anode or cathode. The C value is determined empirically by iterating the calculated results to agree with the experimental data. In this work, it is found that for the anode and cathode, the constants are $C_a = 0.39$ and $C_c = 0.14$ respectively.

Introducing dimensionless variables $u = \frac{r}{R}$, $w = \frac{z}{R}$, $\tau = \frac{\alpha t_d}{R^2}$, and $\theta(u, w, \tau) = \frac{K_t T(r, z, t)}{q.R}$; a more convenient form of equation (4.10) can be written as:

$$\theta(u, w, \tau) = \frac{1}{2} \int_0^\infty J_0(u) J_1(\lambda) \left[e^{(-\lambda w)} \text{erfc} \left(\frac{w}{2\sqrt{\tau}} - \lambda \sqrt{\tau} \right) - e^{(\lambda w)} \text{erfc} \left(\frac{w}{2\sqrt{\tau}} + \lambda \sqrt{\tau} \right) \right] \frac{d\lambda}{\lambda} \quad (4.12)$$

The temperature distribution in equations (4.10) and (4.12) provide a general solution for any radius and depth of the material. However, numerical calculations are difficult to obtain due to the infinite domain and the sinusoidal terms from the Bessel functions. Therefore, the analyses of the equation are only made in the radial and vertical axes, as shown in the following subsections.

4.2.1 Temperature distribution in vertical axis

Along the vertical axis ($u = 0$), the temperature distribution gives [73]:

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$$\theta(0, w, \tau) = 2\sqrt{\tau} \left[\operatorname{ierfc}\left(\frac{w}{2\sqrt{\tau}}\right) - \operatorname{ierfc}\left(\frac{\sqrt{w^2 + 1}}{2\sqrt{\tau}}\right) \right] \quad (4.13)$$

By using the relation between *erfc* and *ierfc* functions, equation (4.13) becomes:

$$\theta(0, w, \tau) = 2\sqrt{\frac{\tau}{\pi}} \exp\left(-\frac{w^2}{4\tau}\right) \left[1 - \exp\left(-\frac{1}{4\tau}\right) \right] + \sqrt{w^2 + 1} \operatorname{erfc}\left(\frac{\sqrt{w^2 + 1}}{2\sqrt{\tau}}\right) - w \operatorname{erfc}\left(\frac{w}{2\sqrt{\tau}}\right) \quad (4.14)$$

Equation (4.14) provides the dimensionless temperature distribution of the material along the vertical axis. The dimensionless temperature versus τ and w are illustrated in Fig. 4.9 and Fig. 4.10 respectively. The value of θ at each point on the vertical axis monotonically increases with time and gradually decreases with increasing distance from the origin. When the time goes to infinity, the temperature distribution attained the steady state with the highest temperature take place at the origin, and given as $\theta(0, 0, \infty) = 1$.

Fig. 4.9 Dimensionless temperature versus τ at different values of w

Fig. 4.10 Dimensionless temperature versus w at different instant of time:

(1) $\tau = 0.05$, (2) $\tau = 0.1$, (3) $\tau = 0.5$, (4) $\tau = 1$, (5) $\tau = 5$, (6) $\tau = \infty$

The maximum temperature of the material always occurs at the center of the surface of the electrode being heated ($u = 0, w = 0$). The maximum temperature can be expressed as:

$$\theta(0,0,\tau) = 2\sqrt{\frac{\tau}{\pi}} \left[1 - \exp\left(-\frac{1}{4\tau}\right) \right] + \operatorname{erfc}\left(\frac{1}{2\sqrt{\tau}}\right) \quad (4.15)$$

4.2.2 Temperature distribution in horizontal axis

Along the radial axis ($w = 0$), equation (4.12) can be written as:

$$\theta(u,0,\tau) = \int_0^\infty \operatorname{erf}(\lambda\sqrt{\tau}) J_0(\lambda u) J_1(\lambda) \frac{d\lambda}{\lambda} \quad (4.16)$$

The relation between erfc and erf functions can be used to expand equation (4.16) into:

$$\begin{aligned} \theta(u,0,\tau) &= \int_0^\infty J_0(\lambda u) J_1(\lambda) \frac{d\lambda}{\lambda} - \int_0^\infty \operatorname{erfc}(\lambda\sqrt{\tau}) J_0(\lambda u) J_1(\lambda) \frac{d\lambda}{\lambda} \\ &= I_1 - I_2 \end{aligned} \quad (4.17)$$

The first integral of equation (4.17) is a steady state term while the second integral is the transient term. An exact solution of the first integral is given by [108]:

$$I_1 = \begin{cases} \frac{2}{\pi} E(u) & ; 0 < u < 1 \\ \frac{2}{\pi} & ; u = 1 \\ \frac{2u}{\pi} [E(u^{-1}) - (1-u^{-2})K(u^{-1})] & ; u > 1 \end{cases} \quad (4.18)$$

K and E are complete elliptic integrals of the first and second kind respectively.

Following the approach taken by Beck [70], the solution for the transient term can be written as:

$$I_2 = \frac{1}{2\sqrt{\pi\tau}} \sum_{i=0}^{\infty} \left\{ \frac{(-1)^i i!}{(2i+1)(4\tau)^i} \sum_{j=1}^{i+1} (i-j+2) \left[\frac{u^{j-1}}{(j-1)!(i-j+2)} \right]^2 \right\} \quad (4.19)$$

Combining the solutions of (4.18) and (4.19) into (4.17), the dimensionless temperature distribution along the radial axis of the material can be calculated. The dimensionless temperature versus τ and u are illustrated in Fig. 4.11 and Fig. 4.12 respectively.

Fig. 4.11 Dimensionless temperature versus τ at different values of u

Fig. 4.12 Dimensionless temperature versus u at different instant of time:

(1) $\tau = 0.05$, (2) $\tau = 0.1$, (3) $\tau = 0.5$, (4) $\tau = 1$, (5) $\tau = 5$, (6) $\tau = \infty$

The change in temperature with time for any point on the radial axis has similar trend with the case of the vertical axis. For any instant of time, the highest temperature always occurs at the origin and slowly decreases with increasing distance from the center. Near the boundary of the heat flux, where u is equal to 1, the temperature decreases abruptly and starts to gradually decrease until it reaches zero at infinity.

4.2.3 Model validation with the experimental results

The micro craters from the experiments were analyzed using SEM. The representative results are depicted in Fig. 4.13 for energy input of 50 μJ , 100 μJ , and 150 μJ . The craters were found to be larger for the anode as compared to the cathode.

Fig. 4.13 SEM

The micro craters resulted from the single discharge experiments do not have distinct outline and are not round. Therefore, during the analyses, the measurement points are taken randomly. The distance between the two peaks at the edge of crater is measured at two directions with 90 degrees difference between each other. The diameter of crater is defined as the average of these two values. As for the depth, the points are taken at the maximum distance from the specimen surface. In order to increase the reliability of the data, the experimental works are performed with 10 replications for each energy input setting.

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A typical voltage and current waveform during the discharge are shown in Fig. 4.14. Since only a fraction of the energy input, defined as discharge energy, is used during sparking; only the pulse-on-time portion of the data is used to determine the energy. From each of the waveform acquired, the average voltage (V_a), average current (I_a), and pulse-on-time were calculated. Together with the material properties of the specimen, i.e. average thermal conductivity, average density, average specific heat, and melting temperature; these data were used as an input to calculate the heat flux radius (R), crater's edge temperature (θ_{crater}), and dimensionless time (τ). The crater's edge temperature works as the boundary where the material will be expelled from the entire superheated and a fraction of the molten areas; which is given as:

$$\theta_{crater} = \frac{K_t(T_m - T_0)}{q \cdot R} \quad (4.20)$$

where T_0 is the ambient temperature [K]. The vertical and radial temperature distributions are calculated by using equation (4.14) and (4.17), which are plotted together with the crater's edge temperature (θ_{crater}) to obtain the values of u and w (see Fig. 4.15). These values are then used to approximate the diameter (d), depth (h) and volume (V_{crater}) of the micro crater where the crater volume (V_{crater}) is given as (see Appendix C):

$$V_{crater} = \frac{\pi d^2 h}{8} + \frac{\pi h^3}{6} \quad (4.21)$$

Fig. 4.14 Voltage and current waveform

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Fig. 4.15 The vertical and radial temperature distributions of the anode:
 $V_a = 15.9$ Volts, $I_a = 2.9$ A, $t_d = 593.75$ ns, material = AISI 4140

The flowchart for the calculation of crater diameter, depth, and volume is given in Fig. 4.16.

Fig. 4.16 Flowchart for the calculation of the crater diameter, depth, and volume

The comparisons between the theoretical and experimental results are shown in Fig. 4.17 and Fig. 4.18 for the anode and cathode respectively.

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(a) Diameter versus Energy input

(b) Depth versus Energy input

(c) Volume versus Energy input

Fig. 4.17 Comparison between theoretical and experimental results for anode (specimen: AISI 4140)

(a) Diameter versus Energy input

(b) Depth versus Energy input

(c) Volume versus Energy input

Fig. 4.18 Comparison between theoretical and experimental results for cathode (Specimen: AISI 4140)

The comparisons are made for diameter, depth and volume of micro craters. It is shown in Fig. 4.17 and Fig. 4.18 that the theoretical results for anode and cathode have a close agreement with the experimental results.

Table 3.5 Statistical comparison between the theoretical and experimental results

	Anode			Cathode		
	Diameter	Depth	Volume	Diameter	Depth	Volume
Maximum error [μm]	1.47	0.40	59.48	1.48	0.43	81.59
Average error [μm]	0.67	-0.05	8.98	0.03	0.10	1.15
Standard deviation of error [μm]	0.66	0.21	35.62	0.76	0.22	43.73
Maximum percentage error [%]	8.4	11	23.0	7.9	25.4	19.7
Average percentage error [%]	3.6	0.4	6.6	0.4	5.7	2.7

Notes:

error = experimental value - theoretical value

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

Table 3.5 presents the statistical error of the theoretical results. The comparison showed that the maximum errors for the approximation of crater diameter are 1.47 μm and 1.48 μm for the anode and cathode respectively. As for the crater depth, the maximum errors are found to be 0.4 μm for the anode and 0.43 μm for the cathode. The errors in term of the volumetric removal at the anode are up to 59.48 μm³, and at the cathode up to 81.59 μm³. In average terms, the percentage errors relative to the measurement results are found to be 3.6% for the diameter, 0.4% for the depth, and 6.6% for the volume in the case of the anode. As for the cathode, the average percentage errors are found to be 0.4% for the diameter, 5.7% for the depth, and 2.7% for the volume.

Thus, the comparative error approximation does not reveal any significant differences in the crater prediction between the cathode and the anode. The theoretical models for the anode and the cathode do not differ. The differences between the anode and cathode comparative results given in Table 3.5 are largely due to the measurements of the experimental data. The irregularities in the crater geometry (see Fig. 4.13) may have attributed to the errors.

Based on the experimental results, the theoretical model developed is validated for the approximation of crater geometries at the anode and the cathode. The input energy range of 5 μJ to 150 μJ used in the experimental work is prevalent in micro-EDM.

4.3 Summary

The analytical model of micro-EDM process is explained in this chapter. The existing models are evaluated using numerical method to elucidate the characteristics of each model and to define the appropriate model which provides the closest approximation in relation to the real process. Based on the presented results, Dibitonto's model is shown to be the most appropriate model to provide the initial approximation of the conventional EDM process. Higher accuracy can be introduced by using the heat disk source model with a trade off in longer processing time.

Based on the existing models evaluation, a two dimensional heat transfer for a material subjected to a disk heat source on its surface is used as the foundation for the micro-EDM model development. It is shown from the analysis that the developed analytical model for micro-EDM process is reasonably accurate to predict the single discharge experimental results within 5 μJ to 150 μJ energy discharges. The following chapter will provide the development of an in situ process monitoring and control of micro-EDM.

CHAPTER 5

IN SITU MONITORING OF MICRO-EDM PROCESS

This chapter proposes analytical models of the Micro-EDM process performances, namely MRR, TWR and SR. The method is based on the crater geometry prediction using the theoretical model described in Chapter 4. The model is able to predict the temperature distribution of the anode and cathode using the average voltage, the average current and the pulse-on-time data obtained during the material removal process. The craters resulted from the thermal erosion process are numerically calculated and are used to define the MRR, TWR, and SR. Based on the experimental work, removal, wear, and surface factors are introduced to take into account the effects of undesirable discharge (open, short-circuit, arcing), machining time averaging error, overlapping craters, pockmarks, micro cracks, and reattachment of debris that result from the actual process. Since the computation required the voltage and current input, which are captured in real time; this approach aims to provide a reliable online monitoring system for the micro-EDM process.

In this chapter, the first section deals with the development of MRR, TWR, and SR models based on the crater prediction results using the developed analytical model in Chapter 4. In the second section, a discussion of the accuracy of the monitoring technique is given. A summary of this chapter is presented in the last section.

5.1 Development of the MRR, TWR, and SR models

Based on the developed analytical model for micro-EDM process, the crater dimensional geometry produced from a single discharge can be calculated based using the electrodes properties, the average voltage, the average current and the pulse-on-time data obtained during the material removal process. Fig. 5.1 illustrates the flowchart to determine the crater diameter, crater depth, MRR, and TWR.

Fig. 5.1 Flowchart for the calculation of the crater diameter, depth, MRR and TWR

5.1.1 MRR model

The experimental MRR is defined as the ratio of the total volume removed from the workpiece divided by the total machining time:

$$\text{Experimental MRR} = \frac{V_{wp}}{t_t} \quad (5.1)$$

where, V_{wp} is the total volume removed from the workpiece [μm^3] and t_t is the total machining time [min]. The volume removed from the workpiece is calculated using the image and coordinate measurement in an optical microscope.

The analytical MRR is calculated using the volume of crater removed from the workpiece divided by the total time per discharge (t_m). However, in Micro-EDM machine, a relaxation type pulse generator is generally used, resulting in a unique total time from charging, delay, breakdown, and pulse-on-time for each discharge, prior to the machining condition. In this model, voltage and current waveform reading which covers three to five discharges are taken and the total time per discharge is determined using the average value of these readings over each experimental setting. This value is considered to represent the total time per discharge. Fig. 5.2 shows the voltage and current waveforms which are used to determined the total time per discharge.

Fig. 5.2 Determination of the total time per discharge in Micro-EDM

$V_o = 110$ Volts, Capacitance=3300 pF, Workpiece = AISI 4140, Electrode = Tungsten

Based on the results from the crater prediction using the voltage, current, and pulse-on-time data; the analytical MRR is determined according to the following equation:

$$\text{Analytical MRR} = S_{MRR} \frac{V_{\text{workpiece}}}{t_m} \quad (5.2)$$

where $V_{\text{workpiece}}$ is the crater volume removed from the electrode per discharge [μm^3] and S_{MRR} is the removal factor. The removal factor is introduced since the analytical value will always exceed the experimental value due to the occurrence of undesirable discharge (open, short-circuit, arcing) and machining time averaging error. Based on the experimental results, the S_{MRR} is found by dividing each of the experimental MRR with the corresponding theoretical MRR ($V_{\text{workpiece}}/t_m$), resulting in the average removal factor of 0.0216 (see Appendix D).

5.1.2 TWR model

The experimental TWR is defined as the ratio between the volume of material removed from the electrode (V_{el}) and the volume of material removed from the workpiece (V_{wp}), as follows:

$$\text{Experimental TWR} = \frac{V_{el}}{V_{wp}} \quad (5.3)$$

Fig. 5.3 Electrode tool wear for various depth settings

Fig. 5.3 illustrates the occurrence of tool wear on the electrode after the experiments. The total volume removed from the electrode is calculated based on the shape differences between the initial and final tool. The calculation process consists of two parts. The first part deals with the end wear of the electrode, which is the difference between the initial length and the final length of the electrode after machining. By using the electrode diameter, the volume removed can be calculated using the cylinder volume equation (see Fig. 5.4).

Fig. 5.4 The end wear volume of the electrode

As for the second part, the outline of the electrode is measured after each experiment. The measurement results are then us to reconstruct the corner wear of the electrode by assuming that the wear is symmetrical. The summation of the two parts gives the total actual volume that was eroded from the electrode (see Fig. 5.5).

Fig. 5.5 Reconstruction of the volume eroded at the electrode

Based on the crater prediction results for the anode and cathode, the analytical TWR is determined according to the following equation:

$$\text{Analytical TWR} = S_{TWR} \frac{V_{\text{electrode}}}{V_{\text{workpiece}}} \quad (5.4)$$

where $V_{\text{electrode}}$ is the crater volume removed from the electrode per discharge [μm^3], and S_{TWR} is the wear factor. The wear factor is used to take into account the effect of using tungsten as the electrode which might contribute to the error since cobalt, which has low melting temperature, is used as the binder. Therefore, the use of the melting temperature value may have to be compensated by the existence of cobalt, thereby increases the volume which will be removed from the electrode. The S_{TWR} value is found by dividing each of the experimental TWR with the corresponding theoretical TWR ($V_{\text{electrode}}/V_{\text{workpiece}}$). Based on the analysis, the average S_{TWR} is found to be 1.782 (see Appendix D).

5.1.3 SR model

It is believed that the EDM surface roughness can be theoretically defined using the knowledge of the crater geometry, specifically the crater diameter and depth. By assuming that: 1) each crater is uniform shaped and represented by a spherical cap; 2) the craters are densely packed and do not overlap; 3) there are no pockmarks, micro cracks, and reattachment of debris, and 4) the rims of the craters are flat; the theoretical model for the

Chapter 5

In Situ Monitoring of Micro-EDM Process

micro-EDM surface roughness is developed. The theoretical surface roughness will be used to represent the upper bound for the actual surface roughness since the formulation will give the maximum possible value, either in terms of center line average surface roughness, R_a or maximum peak to valley surface roughness, R_t . R_a and R_t are used since they are the most common way to quantitatively specify the surface roughness.

The cross section of an ideal surface produced by the micro-EDM process is shown in Fig. 5.6. The surface profile consists of a series of circular arcs which are a result of the micro-craters modeled in Chapter 4.

Fig. 5.6 Schematic diagram of the theoretical surface roughness model

Based on the model, the center line can be calculated by:

$$m = \frac{1}{L} \int_0^L z \, dr$$

By calculating the value at $L = \frac{d}{2}$, the center line is found to be:

$$m = - \left\{ \frac{1}{2} \sqrt{S^2 - \frac{d^2}{4}} - \frac{S^2}{d} \tan^{-1} \left[\frac{(-d)}{2\sqrt{S^2 - \frac{d^2}{4}}} \right] \right\} \quad (5.5)$$

where

$$S = \frac{d^2 + 4h^2}{8h} \quad (5.6)$$

The analytical expression of theoretical average roughness R_a is given as:

$$R_a = \frac{1}{L} \int_0^L |z - m| dr$$

$$R_a = -\frac{2}{d} \left[S^2 \tan^{-1} \frac{(-r_1)}{\sqrt{S^2 - r_1^2}} + mr_1 \right] \quad (5.7)$$

where

$$r_1 = \sqrt{S^2 - m^2} \quad (5.8)$$

As for the maximum peak to valley height (R_t), the value is simply given by:

$$R_t = h \quad (5.9)$$

The expressions given in Equation (5.7) and (5.9) will serve as the upper bound conditions. The actual machined surface is a combination of this ideal geometry and a multitude of overlapping craters generated by sparks in an isotropic manner. To take into account the effects of overlapping craters, pockmarks, micro cracks, and reattachment of debris; surface factors have to be assigned for both R_a and R_t . The calculation using the surface factors will be defined as the modified surface roughness which is given as follow:

$$\text{Modified } R_a = S_{Ra} \cdot R_a \quad (5.10)$$

$$\text{Modified } R_t = S_{Rt} \cdot R_t \quad (5.11)$$

Here, S_{Ra} is the correction factor for the theoretical R_a and S_{Rt} is the correction factor for the theoretical R_t . The surface factors are found by dividing each of the experimental SR with the corresponding theoretical SR. Based on the analysis, the surface factors are 0.2985 and 0.3443 for R_a and R_t respectively (see Appendix D).

5.2 Results and Discussion

5.2.1 MRR model validation

The illustrations of the workpiece holes after the experiments are given in Fig. 5.7.

Fig. 5.7 Machined holes against depth settings

The experimental MRR are used to compare against the analytical approximation as shown in Fig. 5.8. The experimental MRR is found to increase marginally with depth setting from 250 μm to 750 μm. The MRR subsequently decreased at 1000 μm depth setting. The reason for the decrease of the MRR at 1000 μm depth setting is due to the occurrence of arcing and short-circuits as observed in the waveforms which became unstable after 800 μm hole depth. The rotation of the electrode to promote flushing is inadequate to remove the debris from the discharge gap, especially at a deep hole depth setting.

Fig. 5.8 Comparison between the experimental and analytical MRR

The analytical MRR shows a comparable trend to the experimental MRR. At 250 μm and 500 μm depth settings, the analytical results are lower as compared to the experimental values. At 750 μm, the values are almost similar. The value subsequently decreased at 1000 μm depth setting, although it still overestimates the experimental values. The maximum variation between the experimental and analytical results is shown at 1000 μm depth setting where the average analytical approximation is 30% higher as compared to the average experimental results. At 250 and 500 μm depth settings, the average analytical approximation is lower by 14% and 22%, respectively. These variations are attributed to the use of the average total time per discharge for three to five consecutive sparks during the analysis. Based on the comparative results, the analytical approximation is able to provide a close approximation of up to 30% variation from the experimental results.

5.2.2 TWR model validation

The comparison between the experimental and analytical TWR is depicted in Fig. 5.9. Although the plot seems to vary with the depth setting, the variations from 250 μm to 1000 μm depth setting are small and it is taken to be fairly constant. At 250 and 750 μm depth setting, the analytical results are lower by 15% and 8%, respectively. However, the analytical results overestimate the experimental values by 20% and 24% at 500 and 1000 μm depth setting, respectively. Based on the comparative results, the analytical approach is

able to provide a reasonably close approximation to the experimental value. The variations are shown to be up to 24% of the experimental data.

Fig. 5.9 Comparison between the experimental and analytical TWR

5.2.3 SR model validation

The surface roughness of the machined surface was analyzed and a typical result is shown in Fig. 5.10. It is shown that multitude of overlapping craters are covering the hole bottom surface of the workpiece. The surface roughness values are analyzed from random areas on the bottom surface of the workpiece. In order to provide more insight on the surface differences, the images of the hole bottom surfaces are captured using SEM. The results for 80 V, 90 V, 100 V, and 110 V settings are depicted in Fig. 5.11. It is apparent from the SEM figures that the molten materials are expelled from the workpiece surfaces violently during sparking and the rest are resolidified on the surfaces due to the cold dielectric liquid. The pockmarks, the results of entrapped gases escaping from the resolidifying material [58], are also apparent from the figures.

Fig. 5.11 SEM pictures of the micro-EDM-ed surfaces. Workpiece : AISI 4140

Based on the physical properties of the material used, and the voltage and current waveforms acquired from the experiments, the crater geometries are predicted in terms of the diameter and the depth (see Fig. 5.1). These values are then used in the surface roughness model for R_a and R_t formulated in Equations (5.10) and (5.11) respectively. The

results based on the average of five replications for each energy input setting are then compared with the experimental results, as depicted in Fig. 5.12.

a. Center line average

b. Maximum peak to valley height

Fig. 5.12 Comparison between the experimental and the predicted surface roughness for AISI 4140

In order to show the reliability of the model, the results in terms of R_a are compared with the calculation results of Mamalis’s [58], Petropoulos’s [59], and Keskin’s [55] models; as shown in Fig. 5.13. The comparisons show that the developed model gives closer approximation to the experimental results as compared to previous models with average and maximum errors of 0.8% and 137 nm respectively. As for Mamalis’s [58], Petropoulos’s [59], and Keskin’s [55] models; the average and maximum errors are found to be 62.6% and 681 nm, 13.1% and 352 nm, and 79.5% and 832 nm respectively.

Fig. 5.13 Comparison between the developed model with Mamalis's [58], Petropoulos's [59], and Keskin's [55] models results (Specimen: AISI 4140)

In order to validate the surface roughness prediction model, experiments using Ti-6Al-4V are performed using similar parameter settings used in the previous experiments for AISI 4140. The SEM pictures of the experimental results are depicted in Fig. 5.14. The experimental surface roughness is measured and used as the reference to conclude the validity of the developed surface roughness model.

The crater geometry is calculated using the electro thermal model and the results are used in the modified surface roughness prediction model to obtain the surface roughness values. These results are then compared with the experimental results (see Fig. 5.15).

a. Center line average

b. Maximum peak to valley height

Fig. 5.15 Comparison between the experimental and the predicted R_a for Ti-6Al-4V

It is evident from Fig. 5.15 that surface roughness increases with discharge energy and the prediction results follow this trend closely. For R_a , the average error between the experimental results and modified surface roughness equation (16) is 6.56%. Similarly for R_t , the average error is 4.5%.

The results in terms of R_a are compared with the calculation results from Mamalis [58], Petropoulos [59], and Keskin [55], as shown in Fig. 5.16. The comparisons show that the developed model results in average error and maximum error of 6.56% and 124 nm

respectively. As for Mamalis’s [58], Petropoulos’s [59], and Keskin’s [55] models; the average error and maximum error are found to be 60% and 678 nm, 8.1% and 311 nm, and 76.8% and 836 nm respectively.

Fig. 5.16 Comparison between the developed model with others by Mamalis [58], Petropoulos [59], and Keskin [55] (Specimen: Ti-6Al-4V)

These results show that the modified surface roughness prediction model is able to predict the R_a and R_t values reasonably. Since the prediction model takes into account the polarity, electrode properties, voltage, current, and pulse-on-time; its results are expected to be valid for any machining parameters within discharge energies of 5 μ J to 150 μ J.

5.3 Tool wear compensation

A tool wear compensation technique is used to show the effectiveness of the developed TWR model. The TWR model calculation results are used as the input compensation of the tool wear in the Z-axis direction. To verify the tool wear compensation outcome, experimental work is carried out with and without the compensation. A comparative analysis is then performed to study the results. The occurrence of tool wear on the electrode after the experiments is illustrated in Fig. 5.17.

Fig. 5.17 Electrode tool wear. Depth setting: 1000 μ m

Based on the analytical TWR calculation results, the Z-Axis compensation is applied to the micro-EDM process. Due to the complexity of the tool wear shape on the tool wear, the compensation are calculated by assuming that the wear occurred only at the end of the electrode and the corner wear is neglected (see Fig. 5.18).

Fig. 5.18 Schematic diagram of the electrode wear

Thus, the equation for the analytical TWR can be rewritten as:

$$\text{Analytical } TWR = \frac{V_e}{V_w} = \frac{\pi \times r_e^2 \times d_e}{\pi \times r_w^2 \times d_w} \tag{5.12}$$

Where r_e is the radius of the electrode, r_w is radius of the hole to be machined; d_e is the length of the electrode being eroded as tool wear and d_w is the required depth of the hole to be machined. Since in the assumption, the radius of both the electrode and the hole are taken to be consistent, the effect of π and radius can be cancelled, thus:

$$d_e = \text{Analytical } TWR \times d_w \tag{5.13}$$

Based on the analytical TWR data, the compensated depth, d_e , is calculated. This Z-Axis compensation is added to the original machining depth and the micro-EDM process was performed for verification purposes. Table 5.1 shows the compensated depth calculation results for various depth setting.

Table 5.1 The compensated depth for various depth setting

Original Depth Setting / μm	Theoretical TWR Average	TWR Correction factor Average	Calculated experimental TWR Average	Correction Depth to be added / μm	New Depth Setting / μm
250	0.050	1.782	0.089	22.141	272.141
500	0.059		0.104	52.102	552.102
750	0.049		0.086	64.339	814.339
1000	0.056		0.099	99.226	1099.226

The flowchart for the tool wear compensation system is shown in Fig. 5.19.

The typical machining results of this method are illustrates in Fig. 5.20.

Based on the experimental results, the compensation method are able to provide a better accuracy in terms of the hole depth as compared to the original process (see Fig. 5.21). The original process results in 7.5% to 10.6% errors in terms of the final hole depth. By using the Z-Axis compensation, the errors are improved to be within 1% to 7.6%.

Fig. 5.21 Comparative analysis between the original process and the compensated machining results

Although the compensation method are able to improve the error by more than 28% relative to the original process, the machining results still differ by approximately 7.5 μm to 19 μm as compared to the intended hole depth. The plausible reason for this is due to the effect of the side over cut. During the calculation at the Z-Axis compensation, the hole diameter is assumed to be similar with the electrode diameter. However, based on the experimental results, the hole diameter is larger by approximately 6.3% (19 μm) as compared to the electrode diameter (300 μm) due to the over cut. By taking this factor into account, the compensation method can be improved.

5.4 Summary

The implementation of the in situ process monitoring and control of micro-EDM is explained in this chapter. The models to predict the MRR, TWR, and SR are developed based on the prediction of crater geometries. The validation process of each model is performed using the experimental observations. The tool wear compensation technique using the developed TWR model is conducted to study the accuracy of the model. The following chapter will provide the conclusions of this research work. The recommendations for the future works are also described.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1 Conclusions

The development of an in situ process monitoring and control system for micro-EDM is one of the essential functions in an automated manufacturing environment. It must monitor the machining conditions in real time and subsequently predict the MRR, TWR, and SR of the micro-EDM process. The predicted results are then used for the adjustment of the electrode motion and process parameters to enhance the process performance. In this thesis, the following conclusions are drawn from the work done:

1. An experimental rig have been designed and built for a single discharge experiment. The experimental rig consists of a 3-axis linear stage to move and control the position of the electrode relative to the workpiece, electrode and workpiece holder, dielectric tank, RC circuit generator, and data acquisition system.
2. An evaluation on the existing analytical models of the EDM process has been carried out. Each model is simulated numerically and compared with the actual process. Dibitonto's model is shown to be the most appropriate model to provide the initial approximation of the conventional EDM process. Its simplicity in using the point heat source approach has led to fast processing time and thus it would be useful to obtain initial approximation of the crater geometries and MRR in the conventional EDM process. However, using the disk heat source approach, a higher accuracy in terms of the crater shape was achieved with a trade off in longer processing time.
3. An analytical model has been developed to approximate the material removal of micro-EDM process. The comparison between the theoretical and experimental results is made for the low energy discharges. The overall trend has shown that the theoretical model developed is valid for the approximation of crater geometry on the anode and cathode in single discharges. The model is able to predict the crater geometry with maximum errors of 1.47 μm for the diameter, 0.43 μm for the depth,

and $81.6 \mu\text{m}^3$ for the volume. The average percentage errors between the theoretical and experimental results are found to be 3.6% for the diameter, 0.4% for the depth, and 6.6% for the volume in the case of the anode. As for the cathode, the average percentage errors are found to be 0.4% for the diameter, 5.7% for the depth, and 2.7% for the volume.

4. The predictive models for the MRR and the TWR have been developed based on the crater prediction results. The model is able to determine the crater volume removed from the anode and cathode using the average voltage, the average current and the pulse-on-time data obtained during the material removal process. Based on the presented results, the analytical MRR approximation is able to provide an approximation to the experimental results with up to 30% variation from the experimental MRR observations. The analytical TWR presents a relatively better approximation with up to 24% variation from the experimental value.
5. The SR model has been developed using the geometrical analysis of the crater prediction. Through the validation process, the average errors of the proposed models for R_a and R_t are found to be 6.56% and 4.5% respectively. Based on these results; the modified surface roughness prediction model is shown to be able to predict the R_a and R_t values reasonably well.
6. The developed TWR model is used in the calculation of the tool wear compensation in the Z-axis direction. The comparison between the experimental and analytical TWR shows that the proposed in situ tool wear monitoring method is able to provide a close approximation to the experimental results. The initial process without compensation results in the error range of 7.5% to 10.6% from the final hole depth. By using the Z-axis compensation technique, the errors are improved to within 1% to 7.6%.

6.2 Future Work

Based on the results of this investigation, future work in the following areas can be extended:

1. Improvisation of the micro-EDM analytical model

Due to the approach carried out in this work, the reliability of the analytical model is highly dependent on the accuracy of the empirical heat flux radius approximation. Emphasis on the heat flux approximation as well as wider energy input range is necessary.

2. Removal, wear, and surface factors

Due to the complexity of the micro-EDM material removal, the removal, wear and surface factors are introduced to take into account the effects of undesirable discharge (open, short-circuit, arcing), machining time averaging error, overlapping craters, pockmarks, micro cracks, and reattachment of debris that result from the actual process. These factors need to be studied further to improve the reliability of the in situ process monitoring methodology.

3. Tool wear compensation

The introduction of the tool wear Z-compensation technique using the TWR results is able to reduce the machining errors to be within 1% to 7.6%. The error is due to the effect of the corner wear and side over cut. Emphasis on the improvement of this method by taking into account the effect of corner wear and side over cut can be made for the future work.

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APPENDIX A

Electro-thermal models

The analysis of the existing electro thermal models is performed using various equations as explained in the corresponding papers. The summary of the equations used, as well as the specific equations for each model are described in this section.

α is thermal diffusivity of the material [m^2/s] which can be written as:

$$\alpha = \frac{K_t}{\rho \cdot C_p} \quad (\text{A.1})$$

In Snoeys's [65], Van Dijck's [64], and Jilani's [48, 71, 72] models, the melting heat is taken into account in the thermal diffusivity formulation (α'), and given as:

$$\alpha' = \frac{K_t}{\rho \left(C_p + \frac{m}{T_m} \right)} \quad (\text{A.2})$$

Where, m is the latent heat of melting [kJ/kg].

Based on the hypothesis of each research work, various assumptions were used to simplify the process. The initial and boundary conditions were assigned to solve the mathematical formulation of the problem.

The heat flux generated in the plasma channel was defined as:

$$q = \begin{cases} \frac{F_c \cdot V \cdot I}{\pi \cdot r_c^2} & ; \text{ Disk heat source} \\ \frac{F_c \cdot V \cdot I}{2 \cdot \pi \cdot r^2} & ; \text{ Point heat source} \end{cases} \quad (\text{A.3})$$

The analyses of the material removal were based upon the assumption that the amount of the molten material at the end of the pulse-on-time is completely removed by the shockwave generated in the dielectric. Therefore, the boundary of resulted crater was taken from the isotherm surface of the melting temperature of the material under consideration. Details of each model are discussed in the following:

Snoeys's model [65]

In this model, a disk heat source was used to simulate the heat input into the cathode surface, which is assumed to be insulated at the outer area. This heat source is assumed to exist during the pulse-on-time, assuming that the fraction of the energy transferred to the cathode is 50% ($F_c=0.5$).

Schematic diagram of Snoeys's EDM model

Based on the assumptions used, the temperature distribution at the cathode was given as:

$$T(r, z, t) = T_0 + \sum_{n=1}^{\infty} \frac{c_n}{2\lambda_n} J_0(\lambda_n r) \left\{ e^{\lambda_n z} \left[\text{erf} \left(\lambda_n \sqrt{\alpha' t} + \frac{z}{2\sqrt{\alpha' t}} \right) - 1 \right] + e^{-\lambda_n z} \left[\text{erf} \left(\lambda_n \sqrt{\alpha' t} - \frac{z}{2\sqrt{\alpha' t}} \right) + 1 \right] \right\} \quad (\text{A.4})$$

Where, T_0 is ambient temperature [K], J_0 is Bessel functions of the first kind of zero order, erf is the error function, and c_n is given as:

$$c_n = \frac{2 \cdot q \cdot r_c \cdot J_1(\lambda_n r_c)}{K_t \lambda_n r_o^2 \cdot J_1^2(\lambda_n r_o)} \quad (\text{A.5})$$

Here, J_1 is Bessel functions of the first kind of first order, r_o is the radius of insulated surface of the workpiece [m], and the roots of λ_n are determined by $J_0(\lambda_n r_o) = 0$ for $n = 1, 2, 3, \dots$

Van Dijck's model [64]

The model which accounts for the two dimensional nature of the heat flow was solved for two cases, finite and infinite dimension in the z direction. However, the latter case was similar with Snoeys's model [65]. Hence, the analyses are only performed for the case of a finite dimension in the z direction, which is the simplified version of the infinite case. The entire electrode and workpiece surfaces were assumed to be insulated outside the heat source. The whole medium was assumed to be initially at ambient temperature and the fraction of the energy transferred to the cathode was taken as 50%.

Schematic diagram of Van Dijk's EDM model

The superposition principle and separation of variables were applied to the partial differential equation and the solution of the temperature distribution was given as:

$$T(r, z, t) = T_0 + \frac{q \cdot r_c}{K_t} \sum_{n=1}^{\infty} a_n J_0(\lambda_n r) \left\{ \sinh(\lambda_n z) + \sum_{m=1}^{\infty} c_{mn} \sin(\mu_m z) \exp[-\alpha'(\lambda_n^2 + \mu_m^2)t] \right\} \quad (A.6)$$

Where

$$a_n = \frac{2J_1(\lambda_n r_c)}{\cosh(\lambda_n l) [\lambda_n r_o J_1(\lambda_n r_o)]^2} \quad (A.7)$$

$$\mu_m = \left(\frac{\pi}{2l} \right) (2m - 1) \quad (A.8)$$

$$c_{mn} = \frac{(-1)^m \lambda_n \cosh(\lambda_n l)}{l(\mu_m^2 + \lambda_n^2)} \quad (A.9)$$

Here, λ_n is the roots of $J_0(\lambda_n r_o) = 0$, and l is the depth of the material [m].

Beck's model [69, 70]

In this model, the material surface was heated over a disk-shaped region centered at the end of the heat flux. The surface was insulated except over the circular region where the heat flux strikes the material surfaces.

Schematic diagram of Beck's EDM model

The temperature distribution was given as:

$$T(r, z, t) = T_i + \frac{2qr_c}{K_i} \left\{ \frac{r_c B(z, t)}{r_o^2} + \sum_{i=1}^{\infty} \frac{C_i(z, t) J_0(\lambda_i r) J_1(\lambda_i r_c)}{2[\lambda_i r_c J_0(\lambda_i r_c)]^2} \right\} \quad (\text{A.10})$$

Where, T_i is the initial temperature [K], r_o is radius of the outer insulated cylinder [m], λ_i is the roots of $J_1(\lambda_i r_o) = 0$, and:

$$B(z, t) = \sqrt{\alpha t} \operatorname{erfc} \left(\frac{z}{2\sqrt{\alpha t}} \right) \quad (\text{A.11})$$

$$C_i(z, t) = e^{-z\lambda_i} \left\{ 1 + \operatorname{erf} \left[\lambda_i \sqrt{\alpha t} - \frac{z}{2\sqrt{\alpha t}} \right] \right\} - e^{z\lambda_i} \operatorname{erfc} \left[\lambda_i \sqrt{\alpha t} + \frac{z}{2\sqrt{\alpha t}} \right] \quad (\text{A.12})$$

Jilani's model [48, 71, 72]

This model assumed that the heat from the plasma channel is transferred to the workpiece or tool only by conduction. About 90% of the total energy liberated is conducted to the discharge gap and it was distributed equally between the anode and cathode ($F_c=50\%$). The plasma channel has been taken to be a disk heat source situated between two semi-infinite bodies (tool and workpiece). The radius of the heat flux was constant regardless of the discharge conditions and the electrode surfaces are completely insulated except for the portion where the heat flux strikes the material surfaces.

Schematic diagram of Jilani's EDM model

The temperature distribution was derived using an infinite number of instantaneous point heat sources distributed round the circle, and it was given as:

$$T(r, z, t) = \frac{q r_c^2}{K_i} \sqrt{\frac{\alpha'}{\pi}} \int_0^t \exp \left[-\frac{r^2}{4\alpha' t + r_c^2} - \frac{z^2}{4\alpha' t} \right] \frac{1}{(4\alpha' t + r_c^2) \sqrt{t}} dt \quad (\text{A.13})$$

In order to reach a reasonable degree of approximation, the model takes into account the effect of plasma channel growth. The heat source diameter was assumed to change with time and given as:

$$T_b = \frac{q \cdot r_c}{K_t \sqrt{\pi}} \tan^{-1} \left[\sqrt{\frac{4\alpha t}{r_c^2}} \right] \quad (\text{A.14})$$

Dibitonto's model [28]

The plasma radius at the cathode was assumed to be much smaller than at the anode. Therefore, the heat source was approximated by a point instead of a disk for conduction into its interior. The energy used in the cathode erosion was assumed to be 18%.

Schematic diagram of Dibitonto's EDM model

The temperature distribution was given as [73]:

$$T(r, z, t) = T_0 + \frac{q \cdot r}{K_t} \operatorname{erfc} \left(\frac{r}{2\sqrt{\alpha t}} \right) \quad (\text{A.15})$$

APPENDIX B

Determination of the heat flux radius

Single discharge experimental data of the anode:

Energy Input (uJ)	Pulse-on-time (ns)	Crater		
		Diameter (um)	Depth (um)	Volume (um^3)
5	200.00	7.00	1.10	21.8634
5	267.50	7.85	1.13	28.1005
5	202.50	6.75	1.31	24.6161
5	202.50	7.25	1.75	38.9283
5	230.00	7.70	1.24	29.8694
25	468.75	14.80	2.54	227.0629
25	456.25	13.45	1.94	141.6411
25	462.50	14.85	2.02	179.2457
25	325.00	13.65	2.49	190.2734
25	437.50	15.95	2.01	205.0582
50	612.50	17.40	3.01	372.1487
50	643.75	21.85	2.70	516.5111
50	512.50	20.65	3.04	523.7756
50	656.25	22.05	3.71	735.0925
50	731.25	25.50	2.82	731.8364
75	718.75	24.40	2.99	713.0503
75	725.00	23.70	3.11	701.7387
75	631.25	20.35	3.40	573.5063
75	743.75	24.75	2.94	720.5308
75	668.75	22.65	3.21	664.0164
100	818.75	26.45	2.78	775.0080
100	906.25	25.05	2.85	714.4169
100	812.50	24.15	3.31	777.0806
100	781.25	24.50	3.97	968.5609
100	800.00	25.85	3.12	834.6227
125	968.75	30.00	3.29	1181.4280
125	925.00	25.95	3.54	959.3615
125	812.50	26.70	3.77	1083.4720
125	887.50	27.65	3.35	1025.4463
125	818.75	24.00	2.94	678.3181
150	850.00	28.35	3.77	1217.9473
150	1018.75	28.35	3.33	1070.3526
150	900.00	29.50	3.80	1327.3671
150	987.50	31.50	3.66	1451.8107
150	1056.25	29.00	3.28	1101.7291

Single discharge experimental data of the cathode:

Energy Input (uJ)	Pulse-on-time (ns)	Crater		
		Diameter (um)	Depth (um)	Volume (um^3)
5	168.75	6.10	0.89	13.3582
5	200.00	4.60	0.93	8.1104
5	181.25	6.45	0.76	12.6807
5	225.00	6.00	0.77	11.0795
5	200.00	6.50	0.89	15.1178
25	456.25	13.80	1.54	117.0822
25	493.75	12.85	1.35	88.8269
25	400.00	10.20	1.91	81.6841
25	356.52	10.95	1.01	48.0959
25	406.25	9.50	1.69	62.4228
25	393.25	9.30	1.40	48.9871
25	412.50	10.90	1.39	66.2588
50	587.50	15.30	1.24	114.9877
50	543.75	13.80	1.59	121.0138
50	525.00	15.65	1.40	136.0899
50	531.25	14.55	2.23	191.1984
50	487.50	15.10	1.92	175.6215
75	631.25	12.90	1.64	109.4820
75	568.75	16.45	1.51	162.2634
75	675.05	16.65	2.19	243.9140
75	681.25	17.50	2.08	254.8611
75	656.25	17.65	1.96	243.7183
100	812.50	18.45	2.54	348.1166
100	700.00	17.30	1.79	213.3833
100	825.00	19.05	2.01	290.7000
100	806.25	20.30	2.15	353.1326
100	781.25	18.10	1.86	242.6623
125	831.25	24.65	3.00	729.9756
125	893.75	20.80	2.75	478.1069
125	900.00	20.45	2.60	436.1949
125	831.25	16.95	1.32	150.1312
125	850.00	17.25	1.64	193.9477
150	906.25	25.55	2.91	758.8955
150	856.25	22.55	3.20	656.1604
150	968.75	21.35	2.96	543.4224
150	900.00	18.50	2.36	324.0693
150	912.50	19.70	1.78	274.2296

The heat flux diameter, both for the anode and cathode, are determined using the diameter of craters data from the single discharge experiments. By assuming that the heat flux diameter is close to the crater diameter, the heat flux is determined using the power regression of the experimental data.

Hence:

$$R_{\text{anode}} = 0.0284 t_d^{0.9115} \quad [\mu\text{m}]$$

$$R_{\text{cathode}} = 0.0425 t_d^{0.8095} \quad [\mu\text{m}]$$

APPENDIX C

Derivation of the micro crater volume

The micro crater can be simplified by using a spherical cap/segment where the crater is shown as the red region.

Where:

R : The Radius of the sphere

b : The distance from the center of the sphere to the start of the segment

h : The distance from the segment to the bottom of the sphere (depth of crater)

a : The radius of the segment (radius of crater)

r : The radius parallel to the segment

y : The height from the center of sphere

The relationship between r, y, and R can be written as follow:

$$R^2 = r^2 + y^2 \quad (\text{B.1})$$

The crater volume can be derived by using the integral equation:

$$\begin{aligned} V &= \pi \int_{-(b+h)}^{-b} r^2 dy \\ &= \pi \int_{-(b+h)}^{-b} (R^2 - y^2) dy \\ &= \pi \left[yR^2 - \frac{1}{3}y^3 \right]_{-(b+h)}^{-b} \end{aligned}$$

$$V = \pi \left[\left(-bR^2 + \frac{1}{3}b^3 \right) - \left(-R^2(b+h) + \frac{1}{3}(b+h)^3 \right) \right] = \pi \left[R^2h - b^2h - bh^2 - \frac{1}{3}h^3 \right] \quad (\text{B.2})$$

The relationships between the various quantities are:

$$a = \sqrt{R^2 + b^2} \quad (\text{B.3})$$

$$b = \frac{a^2 - h^2}{2h} \quad (\text{B.4})$$

$$R = \frac{a^2 + h^2}{2h} \quad (\text{B.5})$$

Substitution of the values in equation (B.2) gives:

$$\begin{aligned} V &= \pi \left[\left(\frac{a^2 + h^2}{2h} \right)^2 h - \left(\frac{a^2 - h^2}{2h} \right)^2 h - \left(\frac{a^2 - h^2}{2h} \right) h^2 - \frac{1}{3}h^3 \right] \\ &= \pi \left[\frac{2a^2h^2 + 2h^4}{4h} - \frac{1}{3}h^3 \right] \\ V &= \frac{1}{2}\pi a^2h^2 + \frac{1}{6}h^3 \end{aligned} \quad (\text{B.6})$$

Parameter a is the crater radius. When the diameter of crater (d) is used instead of its radius, equation (B.6) becomes:

$$V = \frac{1}{8}\pi d^2h^2 + \frac{1}{6}h^3 \quad (\text{B.7})$$

APPENDIX D

Removal, wear and surface factors

Removal factor

Depth [μm]	Average Tm [μs]	Workpiece crater [mm ³]	Electrode crater [mm ³]	Theoretical MRR [mm ³ /min]	Experimental MRR [mm ³ /min]	Exp. MRR /Theo. MRR
250	134.36	2.23E-07	1.26E-08	9.94E-02	2.25E-03	0.0227
250	156.30	2.23E-07	1.18E-08	8.55E-02	2.17E-03	0.0254
250	160.30	2.26E-07	1.05E-08	8.46E-02	2.04E-03	0.0241
250	179.50	2.22E-07	1.09E-08	7.43E-02	1.90E-03	0.0255
250	174.05	2.21E-07	1.00E-08	7.61E-02	2.13E-03	0.0280
500	160.34	2.24E-07	1.40E-08	8.39E-02	2.28E-03	0.0272
500	160.09	2.26E-07	1.44E-08	8.47E-02	2.28E-03	0.0269
500	153.25	2.20E-07	1.32E-08	8.63E-02	2.36E-03	0.0274
500	172.25	2.14E-07	1.07E-08	7.44E-02	2.16E-03	0.0291
750	129.80	2.14E-07	9.83E-09	9.87E-02	2.35E-03	0.0239
750	124.75	2.19E-07	1.16E-08	1.05E-01	2.33E-03	0.0222
750	122.40	2.15E-07	9.98E-09	1.05E-01	2.28E-03	0.0217
750	124.40	2.16E-07	1.06E-08	1.04E-01	2.27E-03	0.0218
750	109.70	2.08E-07	1.00E-08	1.14E-01	2.26E-03	0.0198
1000	120.45	2.21E-07	1.27E-08	1.07E-01	1.54E-03	0.0145
1000	141.75	2.18E-07	1.23E-08	9.34E-02	1.56E-03	0.0168
1000	129.55	2.16E-07	1.30E-08	9.94E-02	1.73E-03	0.0174
1000	135.45	2.18E-07	1.16E-08	1.01E-01	1.38E-03	0.0137
1000	126.45	2.13E-07	1.14E-08	9.20E-02	1.95E-03	0.0212
Average						0.0216

Wear Factor

Depth [μm]	Average Tm [μs]	Workpiece crater [mm ³]	Electrode crater [mm ³]	Theoretical TWR	Experimental TWR	Exp. TWR /Theo. TWR
250	134.36	2.23E-07	1.26E-08	5.68E-02	1.00E-01	1.7695
250	156.30	2.23E-07	1.18E-08	5.29E-02	1.17E-01	2.2221
250	160.30	2.26E-07	1.05E-08	4.64E-02	1.33E-01	2.8706
250	179.50	2.22E-07	1.09E-08	4.91E-02	1.22E-01	2.4915
250	174.05	2.21E-07	1.00E-08	4.54E-02	7.16E-02	1.5762
500	160.34	2.24E-07	1.40E-08	6.26E-02	8.96E-02	1.4314
500	160.09	2.26E-07	1.44E-08	6.35E-02	7.36E-02	1.1601
500	153.25	2.20E-07	1.32E-08	5.98E-02	1.02E-01	1.7027
500	172.25	2.14E-07	1.07E-08	5.00E-02	8.45E-02	1.6899
750	129.80	2.14E-07	9.83E-09	4.60E-02	8.17E-02	1.7744
750	124.75	2.19E-07	1.16E-08	5.29E-02	1.01E-01	1.9082
750	122.40	2.15E-07	9.98E-09	4.65E-02	1.03E-01	2.2098

750	124.40	2.16E-07	1.06E-08	4.90E-02	9.85E-02	2.0085
750	109.70	2.08E-07	1.00E-08	4.82E-02	8.53E-02	1.7710
1000	120.45	2.21E-07	1.27E-08	5.73E-02	9.20E-02	1.6054
1000	141.75	2.18E-07	1.23E-08	5.63E-02	8.98E-02	1.5944
1000	129.55	2.16E-07	1.30E-08	6.04E-02	7.31E-02	1.2107
1000	135.45	2.18E-07	1.16E-08	5.34E-02	8.16E-02	1.5272
1000	126.45	2.13E-07	1.14E-08	5.33E-02	7.09E-02	1.3302
Average						1.782

Surface factor

Workpiece material: AISI 4140

Discharge Energy [uJ]	Exp. Ra	Exp. Rt	Crater diameter [um]	Crater Depth [um]	Theo. Ra [um]	Theo. Rt [um]	Exp. Ra /Theo. Ra	Exp. Rt /Theo. Rt
8.02	0.1804	1.0170	9.9036	2.8602	0.6752	2.8602	0.2672	0.3556
8.24	0.1936	1.0082	9.9304	2.8887	0.6810	2.8887	0.2843	0.3490
8.41	0.2562	1.0492	10.0042	2.8802	0.6804	2.8802	0.3766	0.3643
8.50	0.2004	1.0308	9.8630	2.9222	0.6863	2.9222	0.2920	0.3527
8.25	0.2012	1.0290	10.0806	2.9070	0.6865	2.9070	0.2931	0.3540
10.05	0.2338	1.0680	10.3366	3.0690	0.7204	3.0690	0.3245	0.3480
10.37	0.2002	1.0614	10.3777	3.0819	0.7234	3.0819	0.2767	0.3444
10.36	0.2212	1.0488	10.3812	3.0988	0.7265	3.0988	0.3045	0.3385
10.19	0.2034	1.0434	10.3886	3.0988	0.7267	3.0988	0.2799	0.3367
10.35	0.1872	1.0840	10.4594	3.0925	0.7266	3.0925	0.2577	0.3505
13.16	0.2112	1.0938	10.9024	3.3064	0.7725	3.3064	0.2734	0.3308
13.18	0.2198	1.1072	10.8468	3.3089	0.7720	3.3089	0.2847	0.3346
13.07	0.2528	1.0752	10.9099	3.3102	0.7733	3.3102	0.3269	0.3248
13.08	0.2528	1.1398	10.9175	3.3140	0.7741	3.3140	0.3266	0.3439
13.33	0.2174	1.0872	10.9050	3.3228	0.7755	3.3228	0.2803	0.3272
16.55	0.2484	1.1864	11.3708	3.5179	0.8181	3.5179	0.3036	0.3372
16.83	0.2820	1.2560	11.2675	3.5267	0.8178	3.5267	0.3448	0.3561
16.67	0.2568	1.2106	11.3427	3.5342	0.8205	3.5342	0.3130	0.3425
16.81	0.2330	1.2300	11.3427	3.5342	0.8205	3.5342	0.2840	0.3480
16.94	0.2716	1.2496	11.6120	3.5313	0.8245	3.5313	0.3294	0.3539
Average							0.2985	0.3443