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MODELING AND SIMULATION OF MICRO ELECTRICAL DISCHARGE MACHINING PROCESS

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MODELING AND SIMULATION OF MICRO ELECTRICAL DISCHARGE MACHINING PROCESS

by

Bai Shao

A DISSERTATION

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MODELING AND SIMULATION OF MICRO ELECTRICAL DISCHARGE MACHINING PROCESS

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Micro parts and systems are playing crucial roles in the area of semiconductor, biomedical device, micro fluid devices, automotive, aerospace and so forth. Micro manufacturing is one of the most important technologies in realizing miniaturization. Compared to other micro manufacturing methods, micro-EDM is drawing lots of attention due to its ability to machine complex 3D parts regardless of the hardness of the workpiece material.

Micro-EDM is the cumulative result of numerous single discharges; therefore, it is crucial to understand the single discharge material removal process in micro-EDM. However, due to the stochastic nature and complex process mechanism, micro-EDM, including its material removal mechanism, has not been fully understood. Process modeling is an effective way to learn and predict the process.

This thesis is focused on the modeling and simulation of the single discharge micro-EDM. Firstly, a method based on analytical solution of the heat transfer equation to determine the energy distribution ratio is presented. Energy distribution ratio is a decisive parameter in micro-EDM process, which determines the energy input into the electrode. This method uses experimentally measured crater geometries to calculate the energy
distribution ratio, which is accurate and easy to apply. Secondly, along with the calculated energy distribution ratio and other realistic boundary conditions, a comprehensive thermal model has been studied. The study shows that the simulation results are very close to the experimental measurements after considering the plasma flushing efficiency. Finally, thermal Marangoni effect has been incorporated into the micro-EDM thermal model. Heat transfer and laminar flow have been studied simultaneously. This model is able to simulate the crater formation process. The simulation results prove that Marangoni effect plays an important role in micro-EDM.
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Finally, I dedicate this thesis to my wife Huang and my daughter Yihan. Their love is the most important driving force pushing me to finish my Ph. D.
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CHAPTER 1 INTRODUCTION

1.1 Background

1.1.1 Micro-Manufacturing

Small means less energy and resource cost, lighter, higher efficiency, higher accuracy and more capable in some circumstances. For example, smaller parts use less material and energy to fabricate; smaller size holes on fuel injection nozzle improves the efficiency of the engine; smaller size holes on the ink jet head increase the accuracy of the printing; and only smaller size tools are able to handle the cells and genes in biotechnology. Miniaturization has the potential to change the way people and machines interact with the physical world [1]. Micro-manufacturing is one of the most important technologies in realizing miniaturization, which was gaining more and more attention due to the rapidly growing demand for micro parts and components in the past decades. Especially in the following fields: semiconductor, biomedical device, micro fluid devices, automotive, and aerospace. Essential value-adding micro parts and components can be found in the products such as: hard disk reading cap, connectors, switches, pacemakers, sensors, medical implants, fuel injection nozzles, micro-pump, micro-engines, etc. [2–4]

The dimension of the products that can be categorized to micro-manufacturing should be between 1-999 µm [5,6]; however, the range of this definition varies according to era, person, machining method, type of product, and material. Some of the researchers have already reduced this range to 1-500 um [4]. Due to the extremely small size of the parts and features, it is difficult to use conventional processes directly in micro-manufacturing. However, by adapting the conventional processes and inventing new processes, such as
micro-cutting, micro-EDM, micro-ECM, Electron Beam Machining, Lithography based techniques, micro-Stereolithography, etc., people could successfully fabricate micro parts and building micro systems [6–9]. The micro-manufacturing processes can be classified into subtractive, additive, forming, joining, and hybrid process as conventional manufacturing processes, which are shown in Table 1.1.

Among all the micro-manufacturing processes, Micro-Electro-Mechanical Systems (MEMS) based processes such as photolithography, chemical-etching, plating, LIGA, etc. have already been well developed. MEMS based techniques have been successfully applied in industry for mass production in making sensors, actuators, and micro structures for decades. However, the restrictions of MEMS techniques, such as limited to silicon or silicon like working materials can only fabricate 2D or 2.5D features. Huge capital investments and inevitable cleanroom environments [1,2,8] are limiting their ability to address the emerging needs for various materials, complex 3D geometries, and high accuracies in micro-manufacturing.

None-MEMS-based micro manufacturing processes are developing quickly in meeting the growing demands for micro-manufacturing. Conventional manufacturing methods, which remove material by mechanical force, such as milling, turning, drilling, and grinding, have been adapted for micro machining. In conventional machining methods the chip thickness is proportional to the cutting edge radius, therefore, the cutting edge of the tools need to be very sharp to reduce the unit material removal to realize micro machining. Current technologies are able to manufacture the tools’ cutting edge radius smaller than 1µm for most conventional machining methods, which is necessary for micro machining [1,4,7].
However, due to the large cutting force, the tool and workpiece distortion are inevitable, which decrease the machining capability of micro machining [7,10]. On the other hand, the conventional methods are lack of ability to machine hard-to-cut materials also limits their application in micro-manufacturing.

Table 1.1 Typical methods/processes in micro-manufacturing [11].

<table>
<thead>
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<th>Subtractive processes</th>
<th>Micro-Mechanical Cutting (milling, turning, grinding, polishing, etc.); Micro-EDM; Micro-ECM; Laser Beam Machining; Electron Beam Machining; Photo-chemical-machining; etc.</th>
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<td>Additive processes</td>
<td>Surface coating (CVD, PVD); Direct writing (ink-jet, laser-guided); Micro-casting; Micro-injection moulding; Sintering; Photo-electro-forming; Chemical deposition; Polymer deposition; Stereolithography; etc.</td>
</tr>
<tr>
<td>Deforming processes</td>
<td>Micro-forming (stamping, extrusion, forging, bending, deep drawing, incremental forming, superplastic forming, hydro-forming, etc.); Hot-embossing; Micro/Nano-imprinting; etc.</td>
</tr>
<tr>
<td>Joining processes</td>
<td>Micro-Mechanical-Assembly; Laser-welding; Resistance, Laser, Vacuum Soldering; Bonding; Gluing; etc.</td>
</tr>
<tr>
<td>Hybrid processes</td>
<td>Micro-Laser-ECM; LIGA and LIGA combined with Laser-machining; Micro-EDM and Laser assembly; Shape Deposition and Laser machining; Efab; Laser-assisted-micro-forming; Micro assembly injection moulding; Combined micro-machining and casting; etc.</td>
</tr>
</tbody>
</table>
Because of the inherited advantages of different material removal mechanism, non-traditional manufacturing techniques are playing important roles in micro-manufacturing. Manufacturing processes such as Electrical Discharge Machining (EDM), Electrochemical Machining (ECM), Ultrasonic Machining (USM), Focus Ion Beam (FIB) Machining, Laser Machining, and so forth, have been successfully adapted for micro manufacturing.

1.1.2 EDM and Micro-EDM

Electrical Discharge Machining (EDM) is a nontraditional machining process, which removes electrical conductive material by a series electric sparks between two electrodes submerged in the dielectric fluid. Melting and vaporization of workpiece material caused by the electrical discharge sparks are thought to be the main material removal mechanism in EDM [2,4,12,13]. The distinguished material removal mechanism gives EDM the following major advantages compared to the traditional machining processes:

1. Capable of machining hard-to-cut materials as long as it is electrically conductive.
2. Free of deformation because no cutting force is involved in the machining process.
3. Able to machine high aspect ratio and complex 3D profiles with high accuracy.
4. Machined parts are burr free and high surface quality.

These major advantages make EDM an inevitable process in many industries such as die making, automotive, aerospace, medical devices, etc.

Figure 1.1 shows the schematic of the well accepted EDM process mechanism. By feeding the energized tool electrode towards the workpiece the gap distance between the tool electrode and workpiece electrode is getting smaller and smaller, and the electric field strength in the gap is getting stronger and stronger. When the gap is smaller than a critical
value, the dielectric media is broken-down due to the excessive high electric field strength, then, the spark begins. After the spark begins, a growing plasma channel is formed. The high temperature and high pressure plasma channel melts and evaporates the material of both electrodes during discharge. The plus generator controls the discharge time. After the discharge, part of the melting and evaporated material is flushed away by the dielectric fluid, craters are left on both electrodes, and the dielectric strength is recovered. Because the differences in the material properties and the polarities the workpiece is eroding faster than the tool electrode; therefore, by repeating the discharge cycle, a mirrored surface profile of the tool electrode is left on the workpiece.

Figure 1.1 EDM process mechanism. [2]
Micro-EDMs include die sinking EDM, wire-EDM, EDM drilling and EDM milling are the downscaling version of the corresponding EDM processes. The discharge energy of micro-EDM is in the range of $10^7$ to $10^5$ joules, which is very small compared to macro EDM. Minimized discharge energy in micro-EDM reduces the unit material removal of each pulse, which enables the process to form micro features. Micro-EDM as a complementary process has been used in micro holes drilling, complex 3D machining, micro tool machining, etc. Figure 1.2 shows the micro parts and features fabricated by micro-EDM.

Figure 1.2 (a) $\Omega5\mu$m micro holes [6]. (b) 2.5D micro turbine [14]. (c) Micro 1/8th sphere in square cavity [15]. (d) Micro pagoda [16].
1.2 Research Motivation and Objectives

EDM has been successfully applied in industries for decades since Lazarenko invented the process 70 years ago. Many theoretical and experimental studies have been conducted to understand the process mechanism and improve the process capability. However, the material removal mechanism still hasn’t been fully understood, due to the transient discharge process occurs in a very narrow gap filled with dielectric fluid, and involves melting and vaporization of the electrodes, thus causing extreme difficulty in observation and theoretical analysis [17]. Moreover, in micro-EDM, the discharge energy is much lower, the gap between electrodes is smaller, and the discharge duration is shorter, making it even harder to understand the process.

EDM is the cumulative result of every single discharge, but every discharge is slightly differed from each other due to the machining condition constantly changing. Thus it is very important to understand the single discharge. Electrical energy transfer and thermal process is a well-accepted material removal theory in EDM, thus many theoretical studies are focusing on thermal modeling of the EDM process [18]. Also, the application of thermal model in micro-EDM is also gaining very encouraging results [19]. However, the main error of the models is caused by using inaccurate parameters (energy distribution ratio), oversimplified boundary conditions (uniform distributed heat source), and average physical properties. Therefore, by fixing these problems, a comprehensive model is able to maximize the potential of the thermal theory in micro-EDM.

Thermal models based on superheating theory are studied extensively in the EDM single discharge simulation. Heat transfer is the dominate physics in the models. However, the
thermal models neglect other physics in the process, and can only solve the temperature distribution. Moreover, experimental observations show contradictions to the superheating theory. A new model is awaited to simulating the crater formation as well as the material removal process.

To expand the application of micro-EDM in micro-manufacturing, a better understanding of the micro-EDM process is necessary. Single discharge modeling is essential to understanding the micro-EDM process, and performs simulation on parametric studies in process optimization. The objectives of this thesis are as follows:

1. Determine the discharge energy distribution ratio analytically, based on the thermal model and the measured crater geometries.

2. Develop a comprehensive thermal model based on the superheating theory which uses realistic boundary conditions such as Gaussian distributed heat flux, temperature dependent thermal properties and expanding plasma radius. Besides, recorded voltage and current data are used as input in the simulation.

3. Propose a crater formation model based on the Marangoni effect. In this model, Marangoni convection is considered to be the dominant driven force in the melt pool. Heat transfer and fluid flow have been studied simultaneously.

4. Solve the analytical models by Finite Element Analysis (FEA), and compare the simulation results with experiments.
1.3 Thesis Organization

Chapter 2 gives a literature review related to the development of EDM particular in pulse generator, dielectric fluid, electrode shape, hybrid machining and micro-EDM. A review of the progress in EDM and micro-EDM modeling is also presented.

Chapter 3 presents the experimental study on the single spark micro-EDM. The experimental conditions and the techniques for data acquisition and data processing are included. The results of the experiments and its analysis have been reported.

Chapter 4 presents an analytical method to determine the discharge energy distribution ratio. The discharge energy distribution ratio is a crucial parameter in EDM and micro-EDM modeling; however, a simple and accurate method to determine this ratio is needed. This analytical method solves the discharge energy distribution ratio based on the thermal model and crater geometries. Compared to previous methods, no transducer and complicated experimental setup are involved in this method.

Chapter 5 introduces a comprehensive micro-EDM thermal-electrical model. Expanding Gaussian’s distributed heat flux, temperature dependent thermal-physical properties, and time dependent discharge power are applied in this model. Superheating is assumed to be the main material removal mechanism. With consideration of the plasma flushing efficiency, the simulation results are very close to the experiments.

Chapter 6 consists of the simulation of the micro-EDM process which incorporates Marangoni effect into the thermal-electrical model. Marangoni convection is induced by the temperature gradient caused by the plasma heating. Heat transfer and hydrodynamic
have been studied simultaneously. The simulation results suggest that Marangoni effect plays an important role in the micro-EDM process.

Chapter 7 concludes the research work in this thesis and makes some suggestions for future work.
CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter reviews the development of the EDM process and its scaling down version micro-EDM in section 2.2. The literatures of modeling EDM and micro-EDM have been reviewed in section 2.3. The limitations of current works have been summarized in section 2.4.

2.2 Development of the EDM process

EDM is one the most extensively used non-conventional machining process in the modern industries [20]. The unique material removal mechanism makes it suitable for machining hard to cut material, making dies and molds, drilling small and deep holes, machining precision and complex shapes, prototyping, etc [17]. The continuously development of the EDM process is essential to keep its competitiveness among other machining processes in the modern industry. In this section, the development of EDM in pulse generator, dielectric fluid, electrode shape, hybrid machining and micro machining have been reviewed.

2.2.1 Pulse generator

Pulse generator is a critical component in EDM because it generates the energy that removes the material. Besides, the characteristics of the wave form include pulse on time, pulse off time, duty cycle, voltage, and current have significant affects to the machining process [21,22]. Relaxation type pulse generator and transistor type pulse generator are the
two most commonly used pulse generators in the EDM equipment. The schematic of these two pulse generators are shown in Figure 2.1.

![Schematic of pulse generators](image)

**Figure 2.1** (a) Relaxation type pulse generator. (b) Transistor type pulse generator. [23]

Relaxation type pulse generator has a longer history. It is based on the charging and discharging of the capacitor that is connected to the DC power supply. The relaxation pulse generator is simple and reliable, but it is hard to control the pulse energy, the material remove rate (MRR) is low, the surface finish is not uniform, and the surface damage occurs [23–25]. With the development of the power transistors, the relaxation type has been replaced by transistor type in most EDM applications. Because the transistor type pulse generator is easy to control and more efficient. However, the pulse produced by the relaxation pulse generator is high in peak current value and short in duration which is suitable for finishing and micro-EDM. The existence of stray capacitance and pulse ignition delay time makes it difficult to obtain significantly short pulse duration with
constant pulse energy by using the transistor type pulse generator [26]. Because there is no capacitor in the transistor type pulse generator, the pulse frequency can be increased dramatically without charging the capacitor. Therefore, it is more efficient by using the transistor type pulse generator in EDM equipment, and by controlling the on and off of the transistor, the machining process can be easily controlled.

2.2.2 Dielectric fluid

The phenomena of electrical discharge between electrodes have been first recorded back in 1694. However, EDM has not become a machining process until the discovery of the dielectric fluid’s decisive role in early 1940s [27]. The presence of dielectric fluid in the discharge gap increases the efficiency and stabilizes the discharge process. The functions of dielectric fluid include: insulating the electrodes, cool down the discharge area, and flush the debris.

Hydrocarbon based oil has been widely applied as dielectric fluid in EDM. The low conductivity of oil results in small discharge gap and high accuracy. However, 1) the localized high temperature during discharge decomposes the hydrocarbon based dielectric fluid and releases harmful vapor (CO and CH₄) [28]; 2) oil-decomposed carbon concentrate on the anode surface unstable the process [29]; 3) the inflammability of the dielectric oil is also a serious safety concern [30]. Therefore, using water as an alternative dielectric fluid has been studied in the last 30 years.

Compared to using hydrocarbon based dielectric, using water based dielectric is less accurate, and less productive. The low accuracy is because of the low resistivity of water enlarging the discharge gap [4]. The low productivity is because of water having less
restriction to the plasma channel due to the low viscosity, thus reducing the energy density, and the MRR is decreasing as a consequence [31]. However, under some special situations, by using deionized water or even tap water may result in higher MRR, such as machining Ti-6Al-4V [32] and micro holes drilling [33].

Using liquid as dielectric media has never been questioned until the study of using gas as dielectric in EDM has been conducted [34]. By comparing the single discharge in liquid and air reveals that volumes of material been melted are the same. However the melted material in gas is reattached to the workpiece after the discharge [35]. Therefore, dry EDM is developed based on the idea of using high pressure air as dielectric to blow away the molten material. The gas jet blows away the melting material and cools down the discharge spot. The study shows that the MRR of dry EDM is low, but the tool wear ratio (TWR) is almost to zero. By mixing gas and liquid, near dry EDM using the high pressure mist as dielectric media has also been studied [36]. The MRR has been increased significantly by using mist compared to gas.

Instead of changing the dielectric fluid, mixing conductive powders to the dielectric is another effective way to improve the process capability. This process is called powder mixed EDM (PM-EDM). Different types of fine abrasive powders have been added to the dielectric fluid, such as aluminum powder [37], silicon powder [38], silicon carbide powder [39], and graphite powder [40]. The advantages of PM-EDM include superior surface finish, even mirror finish is achievable [41,42], and higher MRR and lower TWR [43]. The surface quality has been increased because the added powder enlarges and widens the plasma channel. As a result the craters formed by the discharge are bigger and shallower,
and consequently the surface roughness is lower. The conductive powders suspended in the dielectric act as a bridge making it easier for discharge to take place. Therefore, the flushing is easier because the electrode gap is wider [44].

2.2.3 Electrode shape

Die sinking EDM, and wire-EDM (WEDM), are the two most commonly used EDMs. The differences between these types of EDM are the shape of the electrode and the movement of the electrode.

![Diagram of die sinking EDM](image)

Figure 2.2 Principle of die sinking EDM. [17]

Die sinking EDM is normally used for making dies. Figure 2.2 shows the principle of the die skinning EDM. The electrode is the reversed geometry of the workpiece. While machining, the workpiece is eroded by feeding the electrode towards to the workpiece. An electrode shape cavity is left after machining. However, in the industry, electrode design is a complex and very time consuming process [45], because of the tool wear, uneven machining, discharge gap and complex geometry. To improve the design of electrode, an
advanced algorithm by reverse simulate the EDM machining process has been presented to compensate the tool wear in the electrode design [46]. Moreover, automatic computer added electrode design tool has been developed to improve the efficiency of the designing process [47].

![WEDM Setup Diagram](image)

**Figure 2.3 Basic setup of WEDM. [17]**

WEDM uses a continuously moving electrical conductive wire as electrode. Figure 2.3 illustrates the basic WEDM setup. Discharge occurs between wire and workpiece, and the wire cuts the workpiece like a sawing machine. By controlling the upper and lower wire guide, the desired shape and accuracy can be achieved [48]. The wire is continuously travelling from the wire spool to the used wire spool, so the diameter of the wire in the machining section is constant.

Generally speaking, WEDM is a high precision process. The unique forming mechanism and the ability to cut any conductive material regardless of its hardness, make WEDM an alternative and sometimes the only alternative to fabricate the stamping and
extrusion tools and dies, fixtures and gauges, aircraft and medical device parts, and grinding wheel form tools [49]. However, wire breakage is a serious problem in the WEDM which occurs in many WEMD applications. When wire rupture happens, it would increase the machining time, decrease the machining accuracy, and the deteriorate the machined surface [50]. Experimental observation shows that the discharge frequency rapidly rises about 5-40 ms before the wire breakage [51]. Based on this special pre-breakage phenomenon, a monitor and control system of preventing the wire breakage has been developed. The system turns off the pulse generator and servo system once the sudden rise of the discharge frequency is detected to prevent the wire breakage. A following study shows the correlation between discharge frequency and wire breakage [52]. The study suggests controlling the discharge frequency at a constant level to prevent wire breakage. A WEDM on-line monitor and control system for preventing the wire breakage has been introduced.

EDM with other forms of electrode have also established their own niche area in manufacturing application. EDM drilling uses a constantly rotated hollow electrode, pumping or sucking dielectric fluid through the internal channel in the electrode [53]. EDM drilling is able to drill high aspect ratio macro- and micro holes in aerospace alloys such as Inconel 718 and Ti–6Al–4V, which are beyond the capabilities of conventional twist drilling process [54]. EDM milling uses simple shape electrode with 3D movement to fabricate complex 3D geometry. EDM milling saves the time and cost on preparing the complex electrodes. However, the volumetric electrode wear ratio in EDM mill is higher than the die-sinking EDM. The wear makes the electrode become shorter during machining.
To solve this problem, a sophisticated method to compensate the tool wear and keep the machining accuracy has been implanted [55,56].

A new so called wire electrical discharge milling method by combing the EDM milling and WEDM has been introduced [57]. The electrode is the moving wire slide along the hemisphere tip with a wire guide, and the tip is doing reciprocating rotation during machining. It solves the problem of tool wear in EDM milling.

2.2.4 Hybrid machining

Hybrid machining process development has been a very hot research topic for many years. By integrating two or more processes together, the advantages offered by individual processes can be further extended. And often, faster and cheap machining can be realized by hybrid process owing to the synergistic effect [2]. The hybrid machining processes by combining EDM with other process have gaining a lot of success.

Ultrasonic vibration assistant EDM is one of the hybrid EDM process which applies ultrasonic vibrations to the electrode in the EDM. Studies show that by adding ultrasonic vibration to the electrode increases the slurry circulation and variants the pressure in the discharge gap, which results in higher MRR, better surface finishing, thinner recast layer, less micro-cracks, and higher fatigue resistance [58,59]. Moreover, the ultrasonic vibration can make the discharge process more stable under the narrow gap condition. By combining ultrasonic vibration to the EDM drilling significantly extends the process capability [60–63].

Spark Assisted Chemical Engraving (SACE) or Electrochemical Discharge Machining (ECDM) is another successful hybrid machining process that combines EDM with
electrochemical machining. The schematic setup of the SACE is shown in Figure 2.4. Two electrodes immersed into the electrolyte with a DC power or a pulse power applied between them. The tool electrode (cathode) is hundreds times smaller than the counter-electrode (anode). The tool electrode is only few millimeters dipped into the electrolyte. Owing to the electrolysis process, the gas is decomposed on the tool electrode and forms a thin gas film. The thin gas film insulates between the electrode and the electrolyte. When the voltage applied between the electrodes is higher than the critical value (30V), discharge occurs between the tool electrode and the electrolyte. The thermal energy generated by the sparks and chemical etching are the main reason for material removal on the workpiece [64,65]. SACE extends the capability of electrical machining to nonconductive materials, because the discharge takes place between the electrode and the electrolyte in SACE. Conductive workpiece is not required in SACE which is inevitable in EDM. SACE has been reported to machine non-conductive material such as glass [66], quartz [67], ceramics [68], and composites [69].

Figure 2.4 Schematic of the SACE set-up. [65]
Hybrid machining is a trend in the future manufacturing, since the hybrid machining is capable of reducing the machining cost and improving the machining speed, quality, and capability. Researches show that by combining EDM with other processes is a viable solution to solve some special manufacturing problems. More hybrid EDM processes such as laser guided discharge [70], magnetic field assisted EDM [71], etc, have been developed.

2.2.5 Micro-EDM

Research of micro-EDM has drawn a lot of attention due to the trend of miniaturization, and its ability to machine micro-parts accurately regardless of the workpiece hardness. Micro-EDM has been widely used for machining injection nozzles, spinneret holes for synthetic fibers, electronics and optical devices, micro-mechanical parts, medical parts and surgery tools, and micro-tools [2,4,17]. The overview of micro-EDM capabilities are given in Table 2.1.

Table 2.1 Overview of the micro-EDM capabilities [14].

<table>
<thead>
<tr>
<th>Micro-EDM variant</th>
<th>Geometric complexity</th>
<th>Min. feature size (µm)</th>
<th>Max. aspect ratio</th>
<th>Surface quality Ra (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEDM</td>
<td>3D</td>
<td>3</td>
<td>~100</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>Die-Sinking</td>
<td>3D</td>
<td>~20</td>
<td>~15</td>
<td>0.005-0.3</td>
</tr>
<tr>
<td>Milling</td>
<td>3D</td>
<td>~20</td>
<td>10</td>
<td>0.2-1</td>
</tr>
<tr>
<td>Drilling</td>
<td>2D</td>
<td>5</td>
<td>~25</td>
<td>0.05-0.3</td>
</tr>
<tr>
<td>WEDG</td>
<td>3D</td>
<td>3</td>
<td>30</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Wire Electro-Discharge Grinding (WEDG) [72] is the most strategic development of the Micro-EDM process. WEDG uses metal wire as electrode which slides along a groove in a wire guide, and machines the micro rode like grinding. Figure 2.5 shows the principle of WEDG. The moving wire avoids the problem of electrode wear, so the rod can be machined very accurate. Furthermore, by reducing the discharge energy, a rod as small as 1 µm diameter has been reported [73]. WEDG solves the problem of preparing micro-pins and micro-spindles for micro-EDM.

Figure 2.5 Wire Electro-Discharge Grinding (WEDG) method. [72]

Figure 2.6 WEDG unit on the SMALTEC EM203 micro-EDM machine. [74]
If the tool is pre-machined somewhere then installed on the machine, the tool coordinate and the machine coordinate misalignment is inevitable. Thus the geometric error introduced by the coordinate misalignment is a serious problem, especially in micro-machining. WEDG is a compact system that can be integrated into a machine. WEDG enables the on-the-machine tool making, and consequently reduces the machining error caused by coordinate misalignment to minimum [6]. The very accurate micro electrode on-the-machine fabricated by WEDG makes high precision micro-EDM possible. First the rod is machined on the WEDG unit, and then on the same machine, the machined rod is used as tool by reversing the polarity. Figure 2.6 shows the WEDG unit on the commercial micro-EDM machine SMALTEC EM203.

![Figure 2.6 WEDG unit on SMALTEC EM203](image)

Figure 2.6 WEDG unit on SMALTEC EM203

With the help of advanced CNC controller, WEDG is more powerful. It can be used to fabricate electrodes with various shapes, such as the shapes shown in Figure 2.7. Moreover, the ability of machining any electrically conductive material irrespective of the hardness, for instance tungsten carbide, makes WEDG an ideal process for making micro tools. Tools
made for micro-drilling [75], micro-milling [76], and micro-punching [77] which are machined by WEDG are showing very promising results.

EDM milling is able to machine complex 3D geometry with simple shape electrode controlled by CNC machine. It overcomes the problem of designing and fabrication complex electrodes in die-sinking EDM. Especially in micro level, sometimes it is impossible to machine the electrode for micro die sinking EDM. Therefore, micro-EDM milling is gaining lots of attention in micro machining.

The main issue in micro-EDM milling is the high electrode wear rate which is a result of geometric error and decrease in accuracy [15]. A so called Uniform Wear Method (UWM) which combines the longitudinal tool wear compensation and a special tool path generate algorithm, successfully increaseUs the micro-EDM milling accuracy [78]. UWM uses contouring machining with very small electrode feed for each layer. Only the bottom of the electrode is used for machining. Thus, the end of the electrode is always flat after machining each layer. Furthermore, the to-and-fro scanning path keeps the workpiece surface also flat. By combining the UWM with existing CAD/CAM system, the tool path generation process has been simplified. It makes micro-EDM milling a very powerful process to machining 3D micro complex geometry [79].

Other EDM method such as EDM drilling and WEDM have also been successfully adapted to the micro level. With the help of WEDG, very small electrodes can be machined for micro EDM drilling. Holes as small as 5 µm diameter have been machined [6], as shown in Figure 1.2(a). Micro-WEDM is realized by reducing the wire diameter from 200 µm to 250 µm in WEDM to 10 µm to 50 µm [16].
2.3 Process Modeling of EDM and Micro-EDM

EDM is a very complex stochastic process. Modeling of EDM involves many aspects of the process.

Figure 2.8 proposed a step by step generalized model for EDM. The generalized model breaks down the whole process into individual steps, from discharge location determination to machine control algorithm [80]. However, in the generalized model, some steps are coupled problems, so iterations are involved in the model. For example, the temperature distribution determines the single discharge removal, but reversely the removal process also affects the temperature distribution. Thus, it is not realistic or possible to simulate the EDM process by repeating all the steps in the generalized model. It is useful to simulate only a part of the generalized model to understand the process mechanism, optimize the machine control, predict the machining performance, and planning the process. In this section, the research works on each individual step of the generalized model are reviewed.

Figure 2.8 Generalized model for EDM processes.[80]
2.3.1 Discharge location

In EDM, discharge occurs at a single location where the dielectric strength is lowest. After each discharge a crater will be left. Hence, it is important to determine the discharge location in the process.

It was thought that the discharge takes place at where the gap distance is the narrowest. But experiments show that the distance between electrodes only affect the probability of discharge. Smaller gap has a higher chance for discharge to occur. An experimentally determined discharge probability function has been used to determine the discharge location for a multiple discharges simulation [81].

However, the discharge location determined by discharge probability function of gap width is not accurate enough. Because the concentration of debris, size of the debris and the bubbles generated by discharges significantly affect the dielectric strength in the gap. For example, the location close to the previous discharge location has a higher probability for next discharge, because the debris and the bubbles in the gap reduce the dielectric strength. Consequently, discharges are more likely happening in groups [81].

A method determines the discharge location by comparing the discharge delay time of every voxel composing the tool electrode surface has been proposed [82]. In this method, the discharge delay time was found to be exponentially distributed, and the average discharge delay time $t_{d,ave}$ [μs] is empirically determined under the following machining conditions: copper anode, carbon steel cathode, discharge current of 3 A, discharge duration of 300 ms and open circuit voltage of 120 V. The average discharge delay time
is as a function of the gap width, \( gap \) [mm], concentration of debris particles, \( conc \) [\( \text{mm}^3/\text{mm}^3 \)], machining area, \( area \) [\( \text{mm}^2 \)], and debris diameter, \( r \) [mm] as shown below.

\[
t_{d,\text{ave}} = 8.2 \times 10^{12} \cdot \left( \frac{gap^{0.8} \times r^{2.9}}{area^{1.2} \times conc^{1.6}} \right)
\]  

(2-1)

Then the discharge delay time \( t_d \) can be probabilistically calculated based on the exponential distribution for each voxel. The voxel with the shortest discharge delay time is determined by the discharge location.

2.3.2 Simulation of EDM arc plasma

Simulation of EDM arc plasma provides the boundary conditions to determine the temperature distribution in the EDM process. However, the modeling of arc plasma is extremely complicated, even for the steady state gas discharge.

A varying mass, cylindrical plasma model in water was developed [83]. This model solves the fluid mechanical equation, the energy balance equation and the radiation equation simultaneously. The numerical solution provides plasma radius, temperature, pressure and mass as a function of pulse time for fixed current, gap distance, and the power of the plasma. The result of simulation shows the superheating is the dominant mechanism for removal in EDM. Based on the magneto-hydrodynamic analysis of a steady state DC arc in air [84], the temperature distribution within the gap between electrodes was plotted. The calculation result shows that the highest temperature is about 15000K at the center of plasma.
2.3.3 Simulation of temperature distribution and material removal due to single discharge

The simulation of material removal due to single discharge is the foundation of the whole EDM modeling process, because EDM is the cumulative result of single discharges. However, the single discharge material removal mechanism has not been fully understood. Superheating is the most accepted material removal theory in EDM [17,85]. Other mechanisms such as electrostatic force [86], and joule heating [87] have also been studied.

![Figure 2.9 Incandescence of the removed particles after a discharge.[88]](image)

Superheating theory states that after the discharge occurs, a high temperature and high pressure plasma channel is formed. The high-energy plasma melts both anode and cathode electrodes by conduction. The boiling of the superheated material is suppressed during the discharge duration, and only limited vaporization occurs due to the high pressure. When the discharge stops, the violent plasma collapsing and the bulk boiling ejects part of the melted material into the dielectric. The rest of the melt material re-solidifies in place and
forms a recast layer. The melted material removed after the discharge in EDM has been captured by a high speed camera as shown in Figure 2.9. The optical emission spectrum analysis proves that light is generated by the heated electrode material. In this picture, the trajectories of the ejected material are clearly shown due to the 100 μs exposure time.

Based on the superheating theory, modeling of the single discharge removal has been converted to a heat transfer problem. In the superheating based models, the plasma channel is simplified as a heat source. By solving the transient heat transfer problem, the temperature distribution of the electrode at the end of discharge can be determined. The area where the temperature is higher than the melting temperature is thought to be fully or partially removed.

The research works regard to the thermal modeling of EDM can be traced back to 1971 [89]. Early age EDM thermal models are very simple, due to the limit knowledge to the arc plasma and the lack of computational power. Over simplified assumptions such as constant heat source radius equals to the crater radius, uniform distributed heat flux, constant
material thermophysical properties regardless of temperature, and 50% discharge energy distribution ratio are used in the models [89–92].

The milestone research of EDM modeling carried out by P. Eubank et al. in the late 80s and early 90s proposed the cathode erosion, anode erosion and arc plasma models respectively [83,85,93]. In the cathode erosion model the arc plasma is simplified as a point heat source because the plasma radius is much smaller at the cathode due to the emission of electrons. The point heat source conduction model is shown in Figure 2.14. The point heat source assumption overcomes the issue of determining the boundary conditions. Analytical solution of the temperature distribution is given in Eq.( 2-2 ). Compared to previous EDM thermal model, the simulation result of the point heat source model in MRR and crater radius are much closer to the experimental data [18]. By using energy distribution ratio determined by experimental data is the main reason that point heat source model is more accurate.

\[ T = T_0 + \left( \frac{F_c U I}{2\pi \kappa r} \right) \text{erfc} \left( \frac{r}{2\sqrt{at}} \right) \]  ( 2-2 )

In the anode erosion model, a much complex boundary condition has been applied, which include uniform distributed disk heat source and moving boundary. The anode erosion model is shown in Figure 2.11. This model is capable of showing the melting of materials as well as the re-solidification of the material during longer discharge duration. Simulation results show good agreement with experiments with high energy discharge [93].
Most of the EDM thermal modeling treated EDM as a pure thermal process. The EDM has been simplified as transient heat transfer problems. Analytical assessments show that boundary conditions have significant effect to the temperature distribution estimation. Therefore, it is necessary to use realistic boundary conditions in the modeling process. With the help of advance observation techniques more and more details of the plasma channel have been revealed, such as plasma radius, plasma expansion, the correlation between plasma radius and discharge energy, and plasma energy distribution [88,94,95]. However, realistic boundary conditions are hard to incorporate into the model because with such conditions the analytical solution may not exist.
FEA is a powerful method that can be used to solve differential equations numerically. With the help of FEA, complex geometries and boundary conditions can be applied to the EDM models. A FEA model by considering temperature dependent property and latent heat gives very close simulation results compared to the experiments [97]. Another FEA model applied the Gaussian’s distributed heat source and moving boundary condition [98]. This model not only predicts the temperature distribution, but also capable of predicting the white layer thickness and the depth of the heat affect zone. A parametric study of the EDM process based on the FEA model has been carried out [96]. First the model was valid by comparing the simulated MRR and the crater geometries to the experiments. Then parametric study was carried out by changing the simulation conditions. Finally, the simulation results were used to optimize the machining process. Figure 2.12 shows the simulated single discharge crater.

In micro-EDM, due to a smaller gap, shorter discharge duration and less pulse energy, the discharge process is very hard to observe. A common accepted single discharge removal theory has not been established [2]. A molecular dynamics simulation study of
the micro-EDM crater formation process shows some similarity to the superheating theory [99]. Even without direct evidence, superheating is still the most studied theory in micro-EDM. A heat conduction model with uniform heat source was applied for both anode and cathode crater formation [19]. The pulse energy distribution ratio is determined by iterating the simulation result to agree with experimental data. Another study separated the superheating removal process into the heating phase and the bubble collapsing phase, respectively [100]. It uses volume of fraction method to simulate the dielectric fluid, bubble, and workpiece in the same domain. Both wet EDM and near-dry EDM crater formation processes have been studied.

The superheating theory has gained a lot success in both EDM and micro-EDM modeling. However, contradictory phenomena have been observed. The observation of the single discharge in dielectric oil using X-Ray showed that 85% of the material is removed during the discharge duration [101]. High-speed camera captures the image of flying debris scattered from the discharge points during the discharge [102]. Moreover, the comparison between the single discharge removal in air and in dielectric liquid shows no significant difference for discharge duration longer than 100 µs [103], which indicates the sharp pressure drop of the bubble is not necessary for material removal. These observations are challenging the fundamental of the superheating theory.

2.3.4 Simulation of geometry

Theoretically, by repeating the single discharge simulation based on the discharge location determination algorithm, the final geometry by EDM can be obtained. However, the machining of the actual EDM process is the combination of millions of thousands
discharges. The computational power we have today is not enough to support the multiple sparks simulation as described above. Furthermore, during the multiple discharges the constantly changing debris, bubbles, and dielectric fluid make the problem more complicated.

One research of simulating the multiple discharges [81] discretized the workpiece into hexahedral elements. Then determined the discharge location based on the discharge probability function of the gap distance. An expended Gaussian’s distributed heat flux was applied for calculating the temperature distribution. The temperature distribution was calculated for each simulation time step $\Delta t$. For every hexahedral element which the
temperature is higher than $T_{eq}$ was considered removed after $\Delta t$. This process will repeat until the end of the simulation. Figure 2.13 shows the flow chart of the simulation process.

2.3.5 Gap monitoring and control

Keep a proper gap distance between electrodes during the machining is essential for the dimension accuracy and a high quality surface finish in EDM. Large gap may result in open circuit, and short circuit is more likely to happen in small gap. Only a proper gap will result in high efficient machining. An embedded gap monitoring and control system will keep the gap distance properly during machining, to avoid or minimize the open circuit, harmful arcing, and short circuit. In EDM, the discharge does not occur immediately after the voltage has been turned on, but occurs after the ignition delay time. The voltage and current waveforms shows in Figure 2.14 clearly indicate the ignition delay time. The ignition delay time is longer in large gap, and shorter in small gap. Therefore, ignition delay time $t_d$ is an important indicator of gap distance. Moreover, the average gap voltage is positive related to the gap distance. The gap monitoring and control system controls the tool electrode feed based on comparing the measured average ignition delay time and average gap voltage to the preset reference values. [2,17]

![Figure 2.14 Gap voltage and current waveforms. [17]](image-url)
2.4 Summary

Micro-EDM is capable of making micro features accurately regardless of the hardness. It is playing and important role in micro machining. To extend the application and capability of micro-EDM an accurate model is essential. The model could help to understand the process mechanism, optimize the machine control, predict the machining performance, and planning the process.

Single discharge removal is the most important aspect of the micro-EDM modeling because micro-EDM machining is the cumulative result of millions of thousands single discharge. However, due to small gap, short discharge duration, low discharge energy, and the difficulties in observation, a commonly accepted single discharge model is lacked. The research issues of single discharge micro-EDM modeling are summarized as the following:

1. The heat transfer models are inaccurate because oversimplified assumptions have been applied.

2. Lack of experimental determined discharge energy distribution ratio affects the accuracy of the energy input.

3. The thermal models based on the superheating theory only consists of the thermal process in micro-EDM, which neglects other physical process, and some contradictory observations are reported.
CHAPTER 3 SINGLE SPARK MICRO-EDM EXPERIMENTS

3.1 Introduction

This thesis is focused on modeling the single spark micro-EDM. The models are validated by comparing the experiments data to the simulation results. In this chapter, topics related to experimental setup, experimental procedure, data acquisition and data processing are included.

3.2 Experimental setup

Panasonic MG-ED72W is the platform for the single discharge experiments. The Panasonic MG-ED72W is a commercial 3 axis micro-EDM milling machine equipped with WEDG unit. The relaxation type pulse generator is used in this machine. The following picture shows the actual machine and its components.

![Panasonic MG-ED72W micro-EDM machine](image)

Figure 3.1 Panasonic MG-ED72W micro-EDM machine.
The relaxation type pulse generator is equipped on the MG-ED72W which is able to generate pulse in different energy levels. Five levels of the capacitance (stray capacitance, 10pf, 100pf, 220pf, 3300pf) can be set for machining and the open circuit voltage can be set from 20V – 120V. The polarities of the tool and workpiece can be reversed. By setting the machining parameters accordingly, a wide range of pulse energy level can be achieved.

In the single discharge micro-EDM experiments 304 stainless steel was used as the workpiece, the tool electrode was tungsten wire, and kerosene was used as dielectric. In regards to the machining parameter settings, 3 levels of voltage, 2 levels of capacitance, and positive and negative workpiece polarities were used. Table 3.1 lists the details of the experimental parameters.

<table>
<thead>
<tr>
<th>Table 3.1 Experimental parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece</td>
</tr>
<tr>
<td>Tool electrode (µm)</td>
</tr>
<tr>
<td>Dielectric</td>
</tr>
<tr>
<td>Pulse generator</td>
</tr>
<tr>
<td>Open circuit voltage (V)</td>
</tr>
<tr>
<td>Capacitance (pf)</td>
</tr>
<tr>
<td>Workpiece polarity</td>
</tr>
</tbody>
</table>

3.3 Experimental procedure

To limit the variation of the experiments, a standard experimental procedure was established.

First, sample preparation: 3 mm thick sheet metal was used to prepare the sample workpiece. The sheet metal was cut into 15 mm × 15 mm small pieces first. Then, the
samples were polished on a disc polishing machine to mirror surface for easy observation after the experiment. Distinguish the crater on a rough surface is impossible, because in micro-EDM the size of the crater is smaller than the trench and peak on the rough surface. Therefore, polishing the sample is necessary in preparing the sample.

Second, conducting experiments: In the experiments, Ø125 μm tungsten wires were used as tool electrode. The tungsten wires were grinded down to Ø100 μm by the WEDG unit to reduce the variation of the tool electrodes. Location reference features were machined on the sample surface for easily locating the discharge craters under microscope. During the experiments, the discharge voltage and current waveforms were measured by an oscilloscope.

Third, sample characterization: After the experiments, the samples were cleaned by the ultrasonic cleaner to remove the debris attached on the surface. Then the profiles of the discharge craters were measured by a SPM system.
3.4 Data acquisition and data processing

Figure 3.2 Flow chart of the surface detection.

3.4.1 Generate single craters

The object of experiment is generating single discharge in micro-EDM. However, the MG-ED72W is not able to generate single spark directly. To overcome this problem, the surface detect function (G code: G28.1) was used.

Figure 3.2 is the flow chart showing how surface detect function works. The discharge occurs when the charged tool electrode feeds towards the workpiece. By setting the pulse generator with very low discharge energy, the gap width is very narrow when the discharge happens. The tool is considered touching the workpiece when the discharge occurs. After the discharge is detected, the controller will mark the position and retreat the tool electrode
to a safety height. Because the control cycle time is much longer than the discharge interval, tens of discharges occur before the pulse generator is turned off. The craters formed by discharges are distributed over the electrode surface stochastically. As shown in Figure 3.3, single craters and overlapping craters are observed. Each single crater is corresponding to one discharge. Thus, the single discharge experiments can be realized by the surface detection function.

![Figure 3.3 Craters formed by the surface detection function.](image)

3.4.2 Measuring the current and voltage

The total energy of a single discharge can be determined by the following equation,

\[ P = \sum_{0}^{\frac{t_{on}}{\Delta t}} V(t) \cdot I(t) \cdot \Delta t \]  

(3-1)

where \( V(t) \) and \( I(t) \) are the voltage and current data over the discharge duration; \( t_{on} \) is the pulse on time; \( \Delta t \) is the sampling interval. Tektronix TPS 2024 oscilloscope (2GHz sampling rate per channel, 2500 record length) was used to record the discharge voltage and current data. The wiring schematic of the data acquisition system is shown in Figure 3.4. Tektronix CT-2 current probe was used to convert current signal to voltage signal. The
raw sampling data was saved in a CF card in the oscilloscope and then transferred to PC for post processing.

Figure 3.4 Current and voltage signal acquisition schematic.

Tens of discharges are ignited during the single discharge experiment, thus it is impossible to match the current voltage waveforms to a particular discharge crater. The average current and voltage are calculated to represent the input for each experiment condition. Before calculating the average, the data needs to be aligned. Figure 3.5 shows the data reconstruction process. At the spot where the current changes from 0 to positive value, it will be set as time 0. Then the average values of each sample time are calculated based on the new 0 time. Figure 3.6 shows the average discharge voltage and current waveforms. In the picture, the blue dash lines are the 5 measured current and voltage waveforms, which are stacked together. The red solid lines are their average. The measurements show high repeatability of the current and voltage signals. The variance between each
measurement is small. Hence, by using the averages of the voltage and current to represent individual voltage and current is practical.

Figure 3.5 Data reconstruction process.

Figure 3.6 Average current and voltage waveforms.

By measuring the discharge current and voltage waveforms, the pulse ignition delay and the pulse on time can also be characterized. The $t_d$ and $t_{on}$ in Figure 3.6 indicate the pulse ignition delay and the pulse on time, respectively.
3.4.3 Measuring the crater’s geometry

Veeco Digital Instruments Dimension 3100 Scanning Probe Microscope (SPM) system was used to measure the crater’s 3D profile. It can produce high-resolution, three-dimensional images by scanning a sharp tip over the sample surface. Figure 3.7 is the 3D profile of a crater measured by the SPM system. With the 3D data of the craters, the crater parameters such as radius, depth, and volume can be characterized.

To characterize the craters, a reference plane is critical. The un-machined area in the scanning area can be used as the reference plane. However, the slope introduced by machining and measurement as shown in Figure 3.8 is inevitable. The slope of the surface needs to be compensated. Firstly, the slope was calculated based on the un-deformed area. Secondly, the raw data can be compensated based on the slope. Then the depth and the volume of the crater can be characterized. The depth of the crater is the depth of the lowest spot in the crater, and the volume of the crater is the integral of the depth over the scanning area times the scanning resolution.
The actual discharge crater is not axisymmetric, so by directly measuring the radius by a section view of the crater is inaccurate. Figure 3.9 shows a method by using the zero height counter line to characterize the crater radius. A circle is used to fit the zero counter line, and the radius of the circle is thought to be the radius of the crater.

![Figure 3.9 Crater radius characterization.](image)

**3.5 Results**

In this section, the results of the single discharge micro-EDM experiments include discharge energy, peak current, pulse on time, crater depth, crater radius and crater volume.
are reported. The statistical analysis are included in APPENDIX A. Figures 3.10 to 3.12 show the discharge energy, peak current and pulse on time separately. They are characterized based on the methods introduced in previous section.

Figure 3.10 is the average discharge energies under different experimental conditions. The lowest discharge energy is only 0.41 μJ. ANOVA results show that the discharge energy is significantly affected by voltage, capacity, and polarity. Discharge energy is increased by the increase of capacitance. The discharge energy in average is 18.85 times more by using 3300 pf capacitor than by using 220 pf capacitor. Furthermore, the increase of the open circuit voltage increases the discharge energy. The Energy stored in a capacitor is $\frac{1}{2}CV^2$, where C is the capacitance and V is the open circuit voltage. This equation partially explained why the pulse energy is positive related to the voltage and capacitance. However, the discharge energy is not equal to the energy stored in the capacitor. The stray capacity in the circuit is one of the reasons causing the difference. Moreover, when positive polarity is applied the discharge energy is higher than negative polarity is applied.
Figure 3.11 is showing the peak current of the average current waveform. The peak currents are up to 12.4 A, which indicate the discharge process is very intense. Analysis shows that the peak current is increasing by using the large capacitor. ANOVA shows the significance of the capacity to the peak current. The increase of the open circuit voltage also increases the peak current significantly. Furthermore, the change of polarity shows no significant effect to the peak current.
The pulse on time is shown in Figure 3.12. The pulse on time is around 50 ns when using the 220 pf capacitor, and around 180 ns when using the 3300 pf capacitor. The pulse on time is only significantly affected by the capacitance. Because the discharging time constant of a relaxation type pulse generator is determined by the times of resistance and capacitance. The changes of open circuit voltage and polarity are not showing significant influence to the pulse on time.

The following figures show the results of measured crater depth, crater radius and crater volume respectively. Three craters of each experimental condition were measured by the method shown in section 3.4.3. In Figure 3.13, the plot shows that the craters are deeper when using bigger capacitor. Capacity is the only significant factor affecting the crater depth. Voltage and polarity are not showing significant effect to the crater depth.

![Crater Depth](image)

Figure 3.13 Crater depth.

Figure 3.14 shows the crater radius of different experiment conditions. Voltage and capacity both show significant affect to the crater radius. The craters are getting bigger when increases the open circuit voltage and the capacity. The trend is very similar to the
peak current. Figure 3.15 shows the relationship between the peak current and the crater radius. The $R^2$ of the linear regression is above 0.9, which indicates a strong linear relationship between the crater radius and the peak current.

![Figure 3.14 Crater radius.](image1)

![Figure 3.15 Relationship between crater radius and peak current.](image2)

Figure 3.16 shows the crater volume of different experiment conditions. Voltage and capacity are the two significant factors. The increase of both capacity and open circuit
voltage will increase the crater volume. The crater volume is linear related to the discharge energy as shown in Figure 3.17. The increasing of the discharge energy will result in a bigger size crater.

Figure 3.16 Crater volume.

Figure 3.17 Relationship between crater volume and discharge energy.
3.6 Summary

The single discharge micro-EDM experimental setup, experimental procedure, data acquisition and processing techniques, and the experimental results are reported in this chapter. A commercial micro-EDM machine has been used to perform the experiments. Voltage and current signals, 3D crater profiles were measured by the oscilloscope, and SPM system, respectively. Data processing techniques were applied for more consistent and accurate characterization of the parameters. The results of discharge energy, pulse on time, peak current, crater depth, crater radius, and crater volume have been reported. The results are concluded as follow,

1. The discharge energy and the peak current are increasing with the increase of the open circuit voltage and capacity. When positive polarity is applied, the discharge energy and the peak current are higher.

2. Pulse on time is only affected by the capacity. The discharge duration is longer when larger capacitor is used.

3. Capacity is the only factor significantly affects the crater depth, and crater radius is highly dependent on the peak current.

4. Crater volume is linearly related to the discharge energy. More energy input results in bigger crater size.
CHAPTER 4 DISCHARGE ENERGY DISTRIBUTION RATIO DETERMINATION

4.1 Introduction

In the EDM process, not all the discharge energy dissipates into the workpiece. During the discharge process, the total discharge energy is divided into three parts distributed into anode, into cathode, and into the gap, respectively, as shown in Figure 4.1.

Under most machining condition in EDM, the electrode material removal is proportional to the energy dissipated into the electrode, except the anode removal in macro-EDM when carbon-hydrogen dielectric is used. Because the heat resolved carbon adhesion on the anode surface during the discharge prevents the electrode material been removed [104]. Therefore, it is very important to know how much the discharge energy distributed into the electrode to predict the material removal. The discharge energy distribution ratio is the parameter being used to describe the portion of the total discharge energy that goes into the electrode. It is a crucial parameter in EDM and micro-EDM modeling. Research
show the significant effect of the energy distribution ratio on the thermal simulation [18]. However, this crucial parameter is hard to determine, and the research work related to determine the discharge energy distribution ratio is very limited. Many research works used the same energy distribution ratio value reported more than 30 years ago [85,93], even machining condition is totally different. An easy and accurate method to determine the discharge energy distribution ratio is needed.

In this chapter the previous studies on investigating the discharge energy distribution ratio are reviewed. Then a simple and accurate analytical method to calculate the energy distribution ratio based on the micro-EDM thermal model and the experimentally measured crater geometry is introduced.

4.2 Previous studies on discharge energy distribution ratio

Previous studies determine the discharge energy distribution ratio can be categorized into two methods. One is the temperature rising method, and the other is the empirical method. The details of these two methods are reviewed in this section.

4.2.1 Temperature rising method

In the temperature rising method, thermocouples are used to record the temperature rising on the electrode. The measurements are compared to the calculated temperature rising based on the thermal model with an assumed energy distribution ratio. When the calculation matches the measurement the energy distribution ratio is found.

Figure 4.2 (a) shows the experimental setup for temperature measurement. The electrodes are a piece of copper foil and a copper needle. A constantan wire is connected
to the back of the copper foil to form a copper-constantan thermocouple. The thermocouple and the amplifier are placed in a steel frame shield box to reduce the electromagnetic noise. Single discharges are generated between the copper foil and the copper needle separated by EDM oil. The temperature varying data are recorded by the oscilloscope and stored in a personal computer. The experimental data are compared to the calculation based on the model shown in Figure 4.2 (b). In the model, the arc plasma is assumed to be a constant heat flux which the diameter equals the diameter of the crater. The front and back surfaces of the copper foil are assumed to be adiabatic, and the foil is assumed to be at room temperature for radii larger than 6 mm. The heat transfer model is solved by the finite difference method.

![Diagram](image)

Figure 4.2 (a) Experimental setup for temperature measurement. (b) Temperature calculation model. [104]

The model based calculation is compared to the experimental measurement. By adjusting the energy distribution ratio in the model, the difference between calculation and measurement can be reduced. The energy distribution ratio is found when the calculation best fits the measurement. Figure 4.3 shows the measured and calculated electrode
temperatures when the energy distribution ratio is assumed to be 40%. The inconsistency between the measurement and the calculation before 2 ms is because the malfunction of the amplifier due to the over range, which is caused by the discharge current flow through the thermocouple. After 2 ms, the two curves fit well.

![Graph showing electrode temperature vs. time with labels: copper anode, calculated, and measured. Parameters: i_e=25A, t_e=500 μs, l=1.17mm, X_{Ae}=0.40.](image)

Figure 4.3 One example of measured and calculated transient electrode temperature [104].

The same concept has been applied to investigate the energy distribution ratio in micro-EDM [105]. Due to a much less discharge energy in micro-EDM, plural pulses are ignited to deliver sufficient discharge energy for adequate temperature rise to be measured. However, equalize the energy distribution ratio calculated based on plural pulses to the single discharge is questionable. Furthermore, due to the complexity of the experimental setup, it is hard to apply this method to determine the energy distribution ratio in micro-EDM.
4.2.2 Empirical method

The other method to determine the energy distribution ratio is the empirical method. In the empirical method, a thermal model is used to predict the crater geometry and the removal of the EDM process. By changing the energy distribution ratio in the model, it will affect the model simulation result. Then, energy distribution ratio is determined by iterating the simulation process until the simulation results agree with the experiments. The empirical method has been used to determine the energy distribution ratio for both macro- and micro-EDM. [19,85,93] However, the difference between the energy distribution ratios determined by the empirical method and the temperature rising method indicates the low reliability of the empirical method.

4.3 Determine the discharge energy distribution ratio in micro-EDM analytically

Discharge energy distribution ratio is critical in EDM modeling, but a simple and accurate method to determine this value is lacked. The existing temperature rising method is too complex and the empirical method is not reliable. In this section, a method based on the analytical solution of a thermal model and measured crater depth and radius to determine the discharge energy distribution ratio is introduced. This method provides a simple and accurate alternative to determine the energy distribution ratio in micro-EDM.

4.3.1 Thermal modeling

The axisymmetric semi-infinite body with uniform heat flux conduction model has been used to simulate the micro-EDM material removal process. The schematic of the model is shown in Figure 4.4. The plasma channel is simplified by a constant uniform heat flux,
where $q_0$ is the heat flux and $r_p$ is the plasma radius. The surface outside of the heat flux is assumed to be adiabatic. The temperature of the electrode is the ambient temperature (20°C) at infinite.

![Semi-infinite body with uniform heat flux model](image)

Figure 4.4 Semi-infinite body with uniform heat flux model.

To make this model valid for the micro-EDM process, some assumptions are included, and the main assumptions are listed below:

1. Only one plasma channel is formed for each discharge.
2. Pulse energy is only contributed by the current and voltage during the pulse on time.
3. Pulse energy distributed into the electrode is only by conduction heat transfer.
4. Heat loss from the electrodes by the convection, radiation and removal of debris are negligible.
5. Discharge energy distribution ratio is constant during discharge.
6. Average thermophysical properties of the electrode material are applied over the entire temperature range.
7. Electrode material is homogeneous and isotropic.
8. The latent heat of fusion is considered into the effective heat capacity by the following equation,

\[
C'_p = C_p + \frac{L_f}{\Delta T}
\]  

(4-1)

where \( C'_p \) is the effective heat capacity, \( C_p \) is the average heat capacity, \( L_f \) is the latent heat of fusion and \( \Delta T \) is the temperature difference between melting point temperature of work material and ambient temperature.

9. Superheating is considered to be the main material removal mechanism. The material removal occurs in the end of the discharge, where the material is hotter than the melting temperature is considered removed.

This thermal model is able to represent the discharge process in micro-EDM with the assumptions. Previous research shows this model has the ability to predict the micro-EDM process closely [19].

4.3.2 Mathematical description

The thermal model built in previous section can be described mathematically by the 2D axisymmetric heat transfer partial differential equation (PDE) below,

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t}
\]  

(4-2)

The boundary conditions of this model are

\[
-k \frac{\partial T(r, 0, t)}{\partial z} = \begin{cases} \frac{q_0}{r} & \text{for } 0 \leq r \leq r_p \\ 0 & \text{for } r > r_p \end{cases}
\]  

(4-3)

\[
T(\infty, \infty, t) = 20 \, ^\circ C
\]  

(4-4)

and the initial condition is
\[ T(r, z, 0) = 20 \, ^\circ\text{C} \]  

In the equations \( r \) and \( z \) are radius and depth in cylindrical coordinates; \( t \) is time; \( T \) is temperature; \( k \) is conductivity; \( r_p \) is the plasma radius; \( q_0 \) is the heat flux; \( \rho \) is density; \( \alpha \) is diffusivity which is calculated by the following equation.

\[ \alpha = \frac{k}{\rho C_p} \]  

One important reason to use this model is because the PDE has an analytical solution. The exact solution of this PDE is given by Eq. (4-7), for any \( r \geq 0, z \geq 0 \), and \( t > 0 \),

\[ T(r, z, t) - T_0 = \frac{1}{2} \frac{q_0 r_p}{k} J_0(\frac{\beta r}{r_p}) J_1(\beta) \times \left\{ e^{-\beta z/r_p} \right\} \left[ 1 + \text{erf} \left( \frac{\beta r}{r_p} - \frac{z}{2 \sqrt{\sigma t}} \right) \right] \right. \left. - e^{(\beta z/r_p)} \text{erfc} \left( \frac{\beta r}{r_p} + \frac{z}{2 \sqrt{\sigma t}} \right) \right\} \left[ \frac{d\beta}{\beta} \right] \]  

where \( T(r, z, t) \) is the time varying temperature of the electrode; \( J_0 \) and \( J_1 \) are the Bessel functions of the first kind of the zero and first order, respectively; \( \text{erf()} \) and \( \text{erfc()} \) are error function and complementary error function.

The heat flux \( q_0 \) is the average energy input shown below,

\[ q_0 = \frac{CP}{t_{on} \pi r_p^2} \]  

where \( C \) is the discharge energy distribution ratio; \( P \) is the total discharge energy calculated by Eq. (3-1); \( t_{on} \) is the pulse on time.

4.3.3 Method of determine the energy distribution ratio

If the energy distribution ratio \( C \) and the plasma radius \( r_p \) are known, then Eq. (4-7) can be used for predicting the crater profile in micro-EDM. Based on the superheating
theory, after the discharge where the temperature is hotter than the melting temperature is removed. Therefore, the melting isothermal is equivalent to the crater profile.

The method of determine the energy distribution ratio uses the same equation, but reversely. The concept is first measure the crater profile by the SPM, and then based on the crater profile to calculate the energy distribution ratio and plasma radius. The actual algorithm uses the measured crater radius and crater depth with the equation of temperature distribution in radial axis Eq. (4-9) and the equation of the temperature distribution in vertical axis Eq. (4-10) to solve the energy distribution ratio and plasma radius.

\[
\frac{T(r,0,t) - T_0}{q_0 r_p / k} = \int_{\beta=0}^{\infty} \text{erf} \left( \frac{\beta (\alpha t)^{1/2}}{r_p} \right) \left[ J_0 \left( \frac{\beta r}{r_p} \right) J_1 (\beta) \frac{d\beta}{\beta} \right]
\]  \hspace{1cm} (4-9)

\[
\frac{T(0,z,t) - T_0}{q_0 r_p / k} = 2 \sqrt{\frac{\alpha t}{r_p}} \left[ \text{erf} \left( \frac{z}{2\sqrt{\alpha t}} \right) - \text{erf} \left( \frac{\sqrt{z^2+r_p^2}}{2\sqrt{\alpha t}} \right) \right]
\]  \hspace{1cm} (4-10)

By setting the \( T(r,0,t) = T(0,z,t) = T_m \) at \( r = r_m \) and \( z = z_m \), where \( T_m \) is the melting temperature, and \( r_m \) and \( z_m \) are the measured crater radius and crater depth, respectively. The Eq. (4-9) and (4-10) can be solved simultaneously.

Figure 4.5 shows the solutions of Eq. (4-9) and (4-10) by using the data from experiment measurements. The machining condition is positive polarity, 90V open circuit voltage, and 3300 pf capacitance. The measured crater radius is 4.51 \( \mu m \), crater depth is 1.03 \( \mu m \), discharge energy is 17.28 \( \mu J \), and the pulse on time is 172.2 ns. The thermal-physical properties used in the calculation are listed in Table 4.1.
Table 4.1 Thermal-physical properties of the 304 stainless steel. [106,107]

<table>
<thead>
<tr>
<th>Properties/ parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7538.68 ( (kg/m^3) )</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>25.23 ( (W/(m \cdot K)) )</td>
</tr>
<tr>
<td>Effective heat capacity</td>
<td>0.81 ( (kJ/(kg \cdot K)) )</td>
</tr>
<tr>
<td>Melting temperature</td>
<td>1727 ( (K) )</td>
</tr>
</tbody>
</table>

Figure 4.5 Solutions of Eq. (4-9) and (4-10).

The solution of Eq. (4-9) is only valid when the calculated energy distribution ratio is smaller than 100%. When the plasma radius is too small, even if all the discharge energy is distributed to the electrode, it will not result in a crater radius equal to \( r_m \). Then, when the plasma radius is getting bigger, the required energy to create a crater radius equal to \( r_m \) is becoming less. The least amount of energy needed to melt a crater radius equal to \( r_m \) is when the plasma radius is slightly bigger than \( r_m \). When the plasma radius is getting even bigger, the required amount of energy is becoming more. Because of the increasing of the plasma radius, the intensity of the plasma is getting lower.
The solution of Eq. (4-10) indicates that the bigger the plasma radius, the more energy it needs to create a crater as deep as \( z_m \), because the increasing of the plasma radius will decrease its intensity.

The intersection in Figure 4.5 is the solution for Eq. (4-9) and Eq. (4-10). The energy distribution ratio is 8.2% and the plasma radius is 4.28 \( \mu m \).

4.3.4 Results

![Graph](image)

**Figure 4.6 Comparison between experiments and simulation based on calculated energy distribution ratio and plasma radius.**

The method of determining the energy distribution ratio and the plasma radius are verified by putting the calculated values of \( C \) and \( r_p \) back to the thermal model. The thermal model is solved by COMSOL, which is a commercial FEA software. Heat transfer in solid module has been applied. The melting isothermal solved by the software is compared to the actual crater profile measured by SPM as shown in Figure 4.6. First, the crater radius and depth are compared to the experiments, and the average radius and depth are extremely close to the FEA simulation. The coincidence between the simulation and
experiments on the radius and depth proves that the calculation of energy distribution ratio and plasm radius is correct. The difference between the measured crater profiles and the simulation is because the simulation simply assumes the melting isothermal is the final crater. The actual crater formation process is the combination of plasma channel collapsing, melting material ejecting, dielectric fluid flush, and unremoved material re-solidifies, which is a very stochastic process.

Figure 4.7 Relationship of the crater volume and energy into the workpiece.

The discharge on time in micro-EDM is much shorter than macro-EDM, the carbon concentration which is thought to be the main reason preventing the material removal in macro-EDM is not occurring in the micro-EDM. So the material removal in micro-EDM should be proportional to the energy input into the workpiece. Figure 4.7 shows the correlation between the energy into the workpiece with the crater volume. Compared to Figure 3.17, the 0.95 $R^2$ value in Figure 4.7 is much higher, which indicates a stronger
proportional relationship between the crater volume and energy input as expected. The relationship shown in Figure 4.7 validates the analytical method from another perspective.

The energy distribution ratios are calculated for each experiment, and the results are shown in Figure 4.8. Capacity, voltage, and polarity do not show significant affect to the discharge energy distribution ratio (APPENDIX A). In average, 7.37% of the total energy is distributed to the workpiece when it is positive polarity and 6.78% when it is negative polarity. The average energy distributed to the anode is more than the cathode in this research, but the difference is not significant. The total energy distributed into the electrodes is 14.15%. This value agree with the reported value by the temperature rising method [105]. Our previous research [108] on Ti-6Al-4V micro-EDM discovered that by applying different polarity on the workpiece, it has a significant effect on the energy distribution ratio. The energy distribution ratios of the positive and negative polarity are
9.4% and 3.6%, respectively. The different conclusions indicate that the energy distribution ratio of Ti-6Al-4V is more sensitive to polarity than the 304 stainless steel in micro-EDM.

Figure 4.9 Results of plasma radius.

Figure 4.10 Relationship of the measured crater radius and calculated plasma radius.
Figure 4.9 demonstrates the results of calculated plasma radius. The plasma radius increases with the increasing of open circuit voltage and capacity. The trending of plasma radius to the machining condition is the same as the measured crater radius. Figure 4.10 shows the relationship between these two set of values. Not only the trending is the same, the values of the calculated plasma radius and the measured crater radius are extremely close. The equality of these two values supports the assumption that the plasma radius is equal to the crater radius that has been used in some research works.

4.4 Summary

A method by using analytical solution of the heat transfer equation to determine the discharge energy distribution ratio has been introduced in this chapter. Thermal model with experimental measured crater profile have been used to calculate the energy distribution ratio. This method is verified by FEA simulation. By applying the calculated energy distribution ratio and plasma radius in the thermal model, the simulation results coincidence with the experimental measurements. A very strong linear relationship between the energy into the electrode and the crater volume validates the method from another perspective.

The average discharge energy ratio is 7.37% when the workpiece is positive polarity and 6.78% when the workpiece is negative polarity. Changing the experimental settings does not show significant effect to the energy distribution ratios. Moreover, the ratios calculated by the analytical method agree with the ratios calculated by the temperature rising method proves the accuracy of the method.
On the other hand, this method also solves the plasma radius simultaneously. The calculated plasma radiiuses are extremely close to the measure crater radiiuses. This result supports the assumption of plasma radius equals to the crater radius which has been used in some research.

The method introduced in this chapter is an accurate and easy to apply method compared to the previous methods. It provides an applicable alternative to calculate the energy distribution ratio in the micro-EDM.
CHAPTER 5 THERMAL MODELING

5.1 Introduction

EDM material removal is the combined result of multiple physics, which includes heat transfer, thermodynamics, hydrodynamics, electromagnetics, chemical reaction, and so forth. The material removal process is much more complicated than traditional machining processes. The extremely complicated physical process makes it impossible to model the EDM material removal comprehensively. Moreover, in micro-EDM, the removal process occurs in a smaller gap within a shorter duration, which makes the problem even harder. The results in previous chapter show that the material removal amount is highly dependent on the energy input, which indicates the thermal process is the dominant process in micro-EDM material removal. Therefore, the modeling of micro-EDM material removal process is more focused on the perspective of thermal process. Generally, in the thermal models, the electrical discharge energy is converted as a heat source, and then the heat conducted into the electrodes. Based on the superheating theory, after the discharge the melting isothermal is equivalent to the crater profile.

In the thermal models, the boundary conditions have significant effect to the final crater profile prediction. The development of advanced measurement technology gives us more access to the actual process, which helps on defining the boundary conditions more accurately. In this chapter, a comprehensive thermal model with realistic boundary conditions has been studied. Along with the energy distribution ratio determined in previous chapter, realistic process conditions such as Gaussian’s distributed heat flux, expending plasma radius, temperature dependent thermal properties, and time varying
discharge power are applied in the model. Then the commercial FEA software is used to solve the model, and the simulation is compared to the experiments.

5.2 Thermal modeling

In this section, the comprehensive thermal modeling process is presented. The key of accurate modeling the process is determining the boundary condition based on the real process. Experimental studies on determining the EDM and micro-EDM boundary conditions have been reviewed and the results are included into the thermal model.

5.2.1 Plasma observation

Plasma characterization is extremely hard in EDM and it is even harder in micro-EDM. The knowledge of the plasma is lacked and only few experimental studies exist. The difficulty of plasma characterization is mainly due to the complexity of the process, but also to the experimental difficulties encountered for its characterization. The plasma channel is small, weakly luminous, short duration times, submerged in dielectric fluid, and poorly reproducible due to its stochastic nature.[109]

Imaging is one of the applicable diagnostic to EDM discharge. High speed camera has been used to obtain EDM discharge images. The images help to understand the plasma development during the discharge and the material ejection after the discharge [88,95]. Optical emission spectroscopy is the only applicable plasma diagnostics, which is able to measure the electron temperature, the electron density and the influence of the discharge parameter on the plasma emitted light [109].
Figure 5.1 Schematic drawing of the experimental set-up for imaging [88].

Figure 5.1 shows the experimental setup for gaining the plasma images. A 30,000-fiber endoscope is directly immersed in the dielectric and places a few millimeters away from the discharge location. A small lens is equipped at the tip of the endoscope in order to have enlarged image of the plasma. The shutter of the camera is controlled by the current signal. The current rise is used as the trigger signal to start the diagnostics [88].

Figure 5.2 (a) Typical plasma image (5 µs exposure, 5 µs after breakdown; 24 A, 100 µs, oil). The position of the electrodes is drawn. (b) Contour plot of (a). (c) Intensity profile of (a) along the vertical axis. [88]
Figure 5.2 (a) is a typical plasma image. The light emitting region is close to round or oval, and the diameter increases with the discharge current from 50 to 400 µm for current increase from 6 to 48 A. This observation agrees with our previous conclusion that the plasma diameter is positive, correlated to the peak current. Figure 5.2 (b) and (c) are the counter and profile plot, respectively. They clearly show the intensity of the center light emitting area is higher. The dots in the center of Figure 5.2 (b), and the irregularities in the center of Figure 5.2 (c), are due to the debris blocks the light into the fiber. However, it is still very clear the intensity distribution of the plasma is coincidence with the Gaussian’s distribution as shown in Figure 5.2 (c).

Figure 5.3 Temporal change of plasma generated in dielectric liquid [95].

The plasma radius is gradually increasing during the discharge process in dielectric liquid as shown in Figure 5.3. This is different from the discharge in air, which the plasma completed expansion within 2 µs. It is because the plasma expansion in dielectric liquid is
prevented by the inertia of the liquid [95]. Therefore, in EDM modeling, the heat source expansion should be included.

Gaussian’s distributed expanding plasma is observed in EDM discharge. However, due to the narrower gap and shorter discharge duration, observation of micro-EDM plasma has not yet been reported. In this study, the conclusions of the EDM plasma are also assumed applicable in micro-EDM.

5.2.2 Thermal modeling

![Thermal model diagram]

Figure 5.4 Thermal model.

An axisymmetric thermal model is shown in Figure 5.4 for the micro-EDM. The plasma channel is represented by an expanding Gaussian’s distributed heat source. The surface on along the vertical axis is axisymmetric, and all other surfaces except the heat source area are thought to be adiabatic. The temperature distribution can be calculated. Based on the isothermal, the melting area and the heat affected zone (HAZ) can be identified. The main assumptions for this model are similar to the uniform heat flux model in Chapter 4. The
differences are 1) the temperature dependent thermal-physical properties are applied; 2) latent heat of fusion is directly applied during phase change.

The thermal model uses the same governing equation as the uniform heat flux model in Eq. (4-2). However, the heat source has been changed, as shown below,

$$-k \frac{\partial T(r, 0, t)}{\partial z} = \begin{cases} q(r, t) & \text{for } 0 < r \leq r_p(t) \\ 0 & \text{for } r > r_p(t) \end{cases}$$  \hspace{1cm} (5-1)$$

where the heat flux q is a function of both position and time.

As discussed above, the heat flux follows the Gaussian’s distribution,

$$q(r, t) = 3.1572 \cdot q_o(t) \cdot e^{\left[-3 \left( \frac{r}{r_p(t)} \right)^2 \right]} [110]$$  \hspace{1cm} (5-2)$$

where $q_o(t)$ is the average heat flux. Time dependent current and voltage measurements and the discharge energy distribution ratio calculated before have been used to calculate the time varying average heat flux in Eq. (5-3).

$$q_o(t) = \frac{C \cdot I(t) \cdot U(t)}{\pi r_p^2(t)}$$  \hspace{1cm} (5-3)$$

In Eq. (5-2), 3.1572 is a calculated constant to ensure the energy balance, -3 is an empirical value for describing the shape of the Gaussian’s distribution, and $r_p(t)$ is the time dependent plasma radius. Due to the difficulties in observing the plasma in micro-EDM, an empirical plasma expansion equation Eq. (5-4) used in macro-EDM simulation has been applied.

$$r_p(t) = 0.788 \cdot t^{0.75} [93]$$  \hspace{1cm} (5-4)$$

Applying of temperature dependent thermal properties is another important way to improve the accuracy of the model. Our previous research [111] shows that the simulation
results are significantly different by using temperature dependent thermal properties and average thermal properties. The thermal-physical properties used for this research are shown in Table 5.1.

Table 5.1 Temperature dependent thermal-physical properties of the 304 stainless steel [107].

<table>
<thead>
<tr>
<th>Temperature T (°C)</th>
<th>Density ρ (kg/m³)</th>
<th>Capacity Cp (J/(g·K))</th>
<th>Conductivity λ (W/(m·K))</th>
<th>Diffusivity 10^6 · α (m²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>8020</td>
<td>0.48</td>
<td>14.8</td>
<td>3.85</td>
</tr>
<tr>
<td>100</td>
<td>8000</td>
<td>0.5</td>
<td>15.8</td>
<td>3.95</td>
</tr>
<tr>
<td>200</td>
<td>7950</td>
<td>0.53</td>
<td>17.7</td>
<td>4.2</td>
</tr>
<tr>
<td>300</td>
<td>7903</td>
<td>0.54</td>
<td>18.8</td>
<td>4.4</td>
</tr>
<tr>
<td>400</td>
<td>7855</td>
<td>0.56</td>
<td>20.7</td>
<td>4.7</td>
</tr>
<tr>
<td>500</td>
<td>7805</td>
<td>0.57</td>
<td>21.4</td>
<td>4.8</td>
</tr>
<tr>
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5.3 Results

By applying the realistic boundary and physical conditions, which are Gaussian’s distributed heat flux, time dependent discharge power, expanding plasma radius and temperature dependent thermal-physical properties, to the heat transfer model, the mathematical description of the model becomes very complex, analytical solution is difficult to find. FEA was applied to solve this problem.

The model is simulated by the COMSOL Multiphysics, and heat transfer in solid module is applied. Complex boundary conditions can be easily applied into the FEA model. Figure 5.5 gives the simulated temperature distribution within the workpiece, as well as the melting isothermal. The experimental settings for this simulation are 3300pf, 90V and positive polarity. The melting isothermal is assumed to be equivalent to the crater profile. Figure 5.6 to Figure 5.8 compares the simulation results to the experimental measurements.

Figure 5.5 Simulated temperature distribution.
The simulated crater radii are very close to the measurements for all experimental conditions, as shown in Figure 5.6. On average, the simulated radii are 11% smaller than the measured radius, which is a very good estimation compared to other models [18]. The prediction of the crater radius can be improved by using more accurate plasma expansion model for micro-EDM.

Figure 5.6 Simulated radius V.S. measured radius.

Figure 5.7 compares the crater depth of the simulation and measurements. The simulation overestimates the crater depth for all the experiment conditions. And the model overestimates the crater volume as well in Figure 5.8. The over estimation of the crater profiles are due to the superheating theory assumes that all the material hotter than the melting temperature is removed after discharge. However, this is not the case in the actual micro-EDM material removal process. Experimental observations discovered that a thin layer of re-solid molten material is formed after the micro-EDM [112], which is called
The recast layer is formed by the unremoved molten material attached to the electrode and re-solid after the discharge.

Figure 5.7 Simulated depth V.S. measured depth.

Figure 5.8 Simulated volume V.S. measured volume.
Plasma flush efficiency (PFE) is a parameter used to describe the percentage of the total molten material that has been removed. The following equation shows how to calculate the PFE,

\[ PFE = \frac{V_m}{V_S} \]  

(5-5)

where \( V_m \) is the measured crater volume, and \( V_S \) is the simulated volume. The average PFE in this study is 36.6%.

Figure 5.9 compares the simulations with and without considering the PFE to the experiments. The model predict the radius close to the measurement, so the PFE is thought to only affect the depth of the simulation profile. The new depth when considering the PFE is \( PFE \cdot z \). The difference between original simulation and the simulation with considering PFE is thought to be the recast layer.

![Figure 5.9 Measured crater profiles compare to the simulations. (3300pf, 90V, positive)](image)
Figure 5.10 and Figure 5.11 shows the simulation results when considering the PFE. After considering the PFE, the simulation results are much closer to the measurements. Most of the simulations fall into the range of measurements.

![Crater Depth (µm)](#)

![Crater Volume (µm³)](#)

Figure 5.10 PFE Simulated depth V.S. measured depth.

Figure 5.11 PFE Simulated volume V.S. measured volume.
By introducing the PFE, this model has the ability to predict the recast layer thickness. Figure 5.12 gives the prediction of the recast layer thickness. The predictions show 1) positive polarity produces thicker recast layer, 2) the recast layer thickness increases with the increase of open circuit voltage, and 3) bigger capacitor results in thicker recast layer. The predictions and the trend of the prediction are consistent with the reported micro-EDM recast layer thickness [112].

![Figure 5.12 Predicted recast layer thickness.](image)

### 5.4 Summary

A comprehensive single discharge micro-EDM thermal model has been presented in this chapter. Because the boundary conditions are crucial to the accuracy of the model, the reported realistic boundary conditions such as Gaussian’s distributed expanding heat source, temperature dependent thermal physical properties, and time varying discharge power have been incorporated into the thermal model.
The FEA simulation of the model gives a close prediction of the crater radius, and the average error is about 11% smaller than the measurements. The model over predicts the crater depth and crater volume, but the over predict of the depth and volume is reasonable. Because not all the melt material have been removed after discharge. The unremoved melt material will re-solidify and forms the recast layer. Then, by applying the PFE to the model, the prediction of the crater depth and crater volume is much closer to the experiments, and it gives the model the ability to predict the recast layer thickness.

By applying realistic boundary conditions and accurate process parameters, this comprehensive thermal model is able to predict the single discharge micro-EDM accurately.
CHAPTER 6 MARANGONI EFFECT IN MICRO-EDM

6.1 Introduction

Marangoni effect describes the flow driven by the surface tension gradient. The surface tension gradient can be created by the methods of chemical, electrical and thermal [113]. The Marangoni effect created by temperature gradient induced surface tension gradient is also referring as thermal capillary effect (called here after thermal Marangoni effect) has been excessively studied in the welding process [106,114,115] and laser melting process [116]. Research shows that the Marangoni convection is the dominant driven force for the flow in the weld pool. Figure 6.1 shows the flow pattern of the weld pool caused by the thermal Marangoni effect. A gradient of surface tension is developed due to the temperature gradient. Normally, the temperature coefficient of surface tension is a negative value for metallic liquid, which means higher temperature has lower surface tension [117]. Therefore, the liquid metal flows from the high temperature area (low surface tension) to the low temperature area (high surface tension). An opposite direction subsurface flow is formed to maintain continuity.

Figure 6.1 Marangoni flow in the weld pool.[106]
EDM is a much more intensive process than welding, which will create a higher temperature gradient. Thus, the Marangoni effect should have stronger impact to the melt pool flow in EDM. Though the thermal Marangoni effect has not drawn much attention in EDM modeling and only few research works related to the Marangoni effect in EDM have been published [118,119]. These studies show evidence of Marangoni effect in EDM. Additionally, in micro-EDM, due to the scaling law [120], volume phenomena reduce faster than surface phenomena. Marangoni effect would become the dominant forces in the micro-EDM melt pool flow.

In this chapter a micro-EDM model incorporates Marangoni convection to the thermal process that has been introduced. The heat transfer and the melt pool flow have been studied simultaneously.

6.2 Marangoni effect in micro-EDM

Figure 6.2 Model of Marangoni effect in micro-EDM.
The 2D axisymmetric model of Marangoni effect in micro-EDM is shown in Figure 6.2. The plasma channel is assumed to be an expanding Gaussian’s distributed heat flux. The electrode material is melted by the heat input after the discharge occurs. The thermal model studied in previous chapter shows the temperature distribution along the surface is the highest in the center and decreases along the radial direction. Because the temperature gradient exists on the melt pool surface, the Marangoni convection is formed. The metallic liquid flows from the high temperature region to the low temperature region. Due to inertia force, a rim is formed close to the edge of the pool. After the discharge, the melt pool cools down and re-solid, formed the crater.

To simplify the model, the following assumptions are made:

1. Only one plasma channel is formed for each discharge.

2. Discharge energy is only contributed by the current and voltage. The ratio of energy distributed into the electrode is constant.

3. The heat is transferred into the electrode only by conduction. The heat loss caused by radiation and convection are negligible.

4. The electrode material is homogeneous and isotropic.

5. The liquid metal is incompressible Newtonian flow.

6. Surface tension driven force (Marangoni convection) is the only force acting on the melt pool surface.

After the proper simplification, the model can be described mathematically by the equations given below
\[ \frac{\rho}{D/t} \frac{DV}{D} = -\nabla p + \mu \nabla^2 V \quad (6-1) \]
\[ \nabla \cdot V = 0 \quad (6-2) \]
\[ \rho c_p \frac{DT}{D/t} = k \nabla^2 T \quad (6-3) \]

Eq. (6-1), is the Navier-Stokes equation. To apply the N-S equation over the entire domain, the electrode material is assumed having a very high viscosity when it is in solid state, and after the material temperature is higher than melting temperature, the normal viscosity will be applied. Eq. (6-2) and Eq. (6-3) are the continuity equation and the energy balance equation, respectively.

The boundary conditions of the model are: 1) the bottom \((z=-Z)\) and side \((r=R)\) surfaces are assumed to be adiabatic and non-slip; 2) the centreline \((r=0)\) is axisymmetric; 3) the top \((z=0)\) surface is a free moving surface heated by the heat source in Eq. (6-4), where \(q(r, t)\) is same as Eq. (5-2), and the Marangoni convection is induced by the temperature gradient as shown in Eq. (6-5)

\[ -k \frac{\partial T}{\partial z} = q(r, t) \quad (6-4) \]
\[ \mu \frac{du}{dz} = \frac{dy}{dT} \nabla T \quad [116] \quad (6-5) \]

where \(\mu\) is viscosity, and \(dy/dT\) is the temperature coefficient of surface tension.

6.3 Simulation

6.3.1 Simulation configuration

The model simulation of the Marangoni effect in micro-EDM was also conducted by COMSOL. Unlike previous simulations, only one physics module was applied. To solve this model, three physics modules heat transfer in fluid, laminar flow and moving mesh
have been applied simultaneously. The heat transfer in fluid module solves the energy balance equation, the laminar flow module solves the N-S equation and the continuity equation, and the moving mesh module solves the deformation of the meshes, respectively. The expanding Gaussian’s distributed heat source, time dependent power input, temperature dependent thermal properties and the calculated discharge energy distribution ratio used in Chapter 5 were applied to the heat transfer in fluid module. Marangoni convection induced by the temperature gradient was incorporated to the laminar flow module. The physics properties applied in the simulation are listed in Table 6.1.

Table 6.1 Physical properties applied for simulation. [106,107]

<table>
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<td>Density ((kg/m^3))</td>
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<tr>
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<td>Heat Capacity (J/(kg \cdot K))</td>
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<td>Effective viscosity ((Pa \cdot s))</td>
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<td>Temperature coefficient of surface tension ((N/(m \cdot K)))</td>
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</table>

In this FEA model, the elements of solid and liquid phases were existed in the same domain. To overcome the complexity in calculation, all the elements were assumed to be liquid. A large value of viscosity was assigned to the elements in solid status to eliminate the movement. The function of viscosity to temperature is shown in Figure 6.3.
The simulation duration set for the studies were longer than the pulse on time. Both the heating and cooling process have been included in the simulation.

6.3.2 Simulation results

Simulations were conducted for each experimental setting. Figure 6.4 compares a measured crater to a simulated crater. The simulation inputs are based on experimental measurements. The topology of the simulated crater and the measured crater are very similar. The multi-physics Marangoni effect model not only forms a crater but also forms the rim of the crater, which is a big improvement compares to the thermal model.
Figure 6.5 Simulation of the crater development (3300pf, 90V, positive).

Figure 6.5 reveals the crater formation process by the simulation. The red areas in the pictures are in the liquid state, and the blue areas are in the solid state. The arrows indicate the flow field. From the beginning of the simulation to 172 ns is the heating phase. The discharge energy goes into the electrode. The melt pool is getting bigger and bigger due to conduction and the heat source expansion. Due to the temperature gradient induced surface tension gradient – thermal Marangoni effect is the main reason that the liquid metal flows outward from center along the radial direction. Consequently, the level of the melt pool gets lower in the center. The liquid metal from the center accumulates at the edge of the melt pool, forming a ripple. After the pulse on time, the electrode starts to cool down. However, the size of the melt pool is not shrinking immediately after the heating. This is due to the heat conduction speed being dominated by the diffusivity. After the melt pool
expands to its limit, the liquid metal starts to re-solidify and the red area is getting smaller. Though, the heat input stops after the discharge, the Marangoni convection still drives the melt pool. The shape of the melt pool is continuously deforming, but the change is less and less, until all the liquid metal is turned back to solid. The simulation also shows during the crater formation process, the local flow speed is up to 30 m/s and the surface shear stress caused by the Marangoni effect is up to 20 MPa.

Figure 6.6 compares the crater profile of the simulation and the experiments. The crater depth of the simulation is close to the measured crater depth. The height of the rim is within the range of measurements. However, the simulated crater is significantly smaller than the measured crater in radius. The similarity between the simulated crater and the experimental measured crater suggests that the Marangoni convection plays an important role in micro-EDM.

![Figure 6.6 Crater profiles of the simulation and experiments (3300pf, 90V, positive).](image-url)
Figure 6.7 Crater depth of the simulations and experiments.

Figure 6.8 Crater radius of the simulations and experiments.

Figure 6.7 compares the simulated crater depth to the measured crater depth. The model predictions are close to the experiments when the 3300 pf capacitor is used. When the 220 pf capacitor was used, the model underestimates the crater depth. Figure 6.8 agrees with
the conclusion of Figure 6.6, the model significantly underestimates the crater sizes for all the experiments. The average error of the crater radius is about 52%.

The errors between the simulation and experiments are reasonable because the material removal process is absent in this model. The model is a closed system, only deformation occurs, the total weight is the same before and after the discharge. Moreover, the neglecting of the super high pressure of the plasma channel might also affect the accuracy of the model. Although the simulation results are slightly deviated from the experiments, they still suggest that the Marangoni effect plays an important role in the micro-EDM process. It should be considered in the modeling of micro-EDM.

6.4 Summary

Thermal Marangoni effect has been incorporated into the micro-EDM thermal model. The surface tension gradient induced by the temperature gradient on the melt pool surface drives the melt pool flow. After the heating, the molten material cools down and forms a crater with a rim around.

Heat transfer, laminar flow, and deformation have been studied simultaneously. The heat transfer setting of the simulation is the same as Chapter 5, and the Marangoni effect is incorporated into the laminar flow. The simulation results show that the crater profile changes the most during the heating process. During the cooling process, the profile of the crater continuously changes until all molten material has cooled down. The improvement of this model compared to the thermal model, is its ability to present the crater development process. Moreover, the shape of simulated crater is similar to the actual micro-EDMed crater. However, the model only simulate the deformation process, the mass of the
simulated domain has not changed. Neglecting the super high pressure of the plasma channel and lack of the material removal should be the main reason for the difference between experiments and simulation.

The simulation shows the significant effect of the Marangoni effect in the micro-EDM crater formation process. It should be considered into the future micro-EDM models.
CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORKS

7.1 Conclusions

The objective of this thesis is to build a micro-EDM model to predict the process. First, the single discharge micro-EDM has been experimentally studied. Process parameters and crater profile include discharge energy, peak current, discharge on time, crater radius, crater depth and crater volume have been characterized. The process parameters are used as input for the models, and the crater profile is used to compare with the simulation results. The influences of the experimental settings to the values have been analytically studied.

Second, the discharge energy distribution ratio has been calculated. The energy distribution ratio determines the energy input into the workpiece which significantly affects the accuracy of the model prediction. A method based on the analytical solution of the thermal model and crater profile to calculate the energy distribution ratio has been presented. Compared to previous method, this method is accurate and easy to apply. The average discharge energy ratio is 7.37% when the workpiece is positive polarity and 6.78% when the workpiece is negative polarity.

Then a comprehensive micro-EDM thermal model has been studied. Realistic boundary conditions such as expanding Gaussian’s distributed heat source, temperature dependent thermal-physical properties, and time varying discharge power has been included into the model. The superheating theory is assumed to be the main material removal mechanism. The simulation of the model with considering the plasma flushing efficiency gives a very close prediction of the crater profile compared to the experiments.
Last but not the least, thermal Marangoni effect has been incorporated into the micro-EDM thermal model. The Marangoni convection in micro-EDM is induced by the temperature gradient on the melt pool surface due to the plasma heating. Most of the previous micro-EDM models only considered the thermal process, but this model solves the heat transfer and fluid flow simultaneously. The simulation forms a crater with rim which is similar to the actual micro-EDM craters. Neglecting the high pressure of the plasma channel and lack of material removal could be the main reason for the error.

7.2 Recommendations for future work

1. The micro-EDM material removal mechanism needs to be studied. Superheating theory is still applicable in micro-EDM need to be confirmed. Otherwise, everything built upon the superheating theory is shaky.

2. To improve the micro-EDM thermal model, accurate boundary conditions are the key. Plasma expansion rate and the energy distribution profile are very hard to determine in the micro EDM, but they are playing important roles in the micro-EDM modeling.

3. Study on Marangoni effect in EDM and micro-EDM modeling can be extent further. By applying the plasma channel pressure to the melt pool, and the ejecting of melting material after the discharge could make the model more complete.

4. Incorporating the single discharge model to general micro-EDM model. A complete micro-EDM model is able to give a better prediction of the process performance such as material removal rate, tool ware ratio, recast layer thickness, and so forth.
REFERENCES


APPENDIX A

All the statistical analysis results are shown below. Data are analyzed by Mintab 17.

General Linear Model: discharge energy versus voltage, capacity, polarity

Analysis of Variance

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General Linear Model: peak current versus voltage, capacity, polarity

Analysis of Variance

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General Linear Model: pulse on time versus voltage, capacity, polarity

Analysis of Variance

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General Linear Model: depth versus voltage, capacity, polarity

Analysis of Variance

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General Linear Model: radius versus voltage, capacity, polarity

Analysis of Variance

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Main Effects Plot for radius
Fitted Means

Interaction Plot for radius
Fitted Means
General Linear Model: volume versus voltage, capacity, polarity

Analysis of Variance

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General Linear Model: energy distribution versus voltage, capacity, polarity

Analysis of Variance

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