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].

Subtractive processes	Micro-Mechanical Cutting (milling, turning, grinding, polishing, etc.); Micro-EDM; Micro-ECM; Laser Beam Machining; Electron Beam Machining; Photo-chemical-machining; etc.
Additive processes	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.
Deforming processes	Micro-forming (stamping, extrusion, forging, bending, deep drawing, incremental forming, superplastic forming, hydro-forming, etc.); Hot-embossing; Micro/Nano-imprinting; etc.
Joining processes	Micro-Mechanical-Assembly; Laser-welding; Resistance, Laser, Vacuum Soldering; Bonding; Gluing; etc.
Hybrid processes	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.

Because of the inherited advantages of different material removal mechanism, none-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.

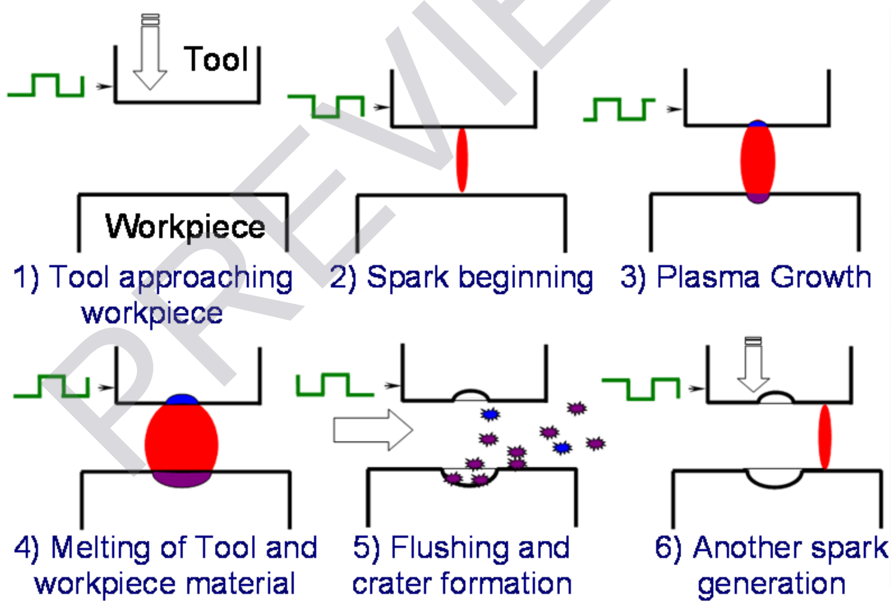
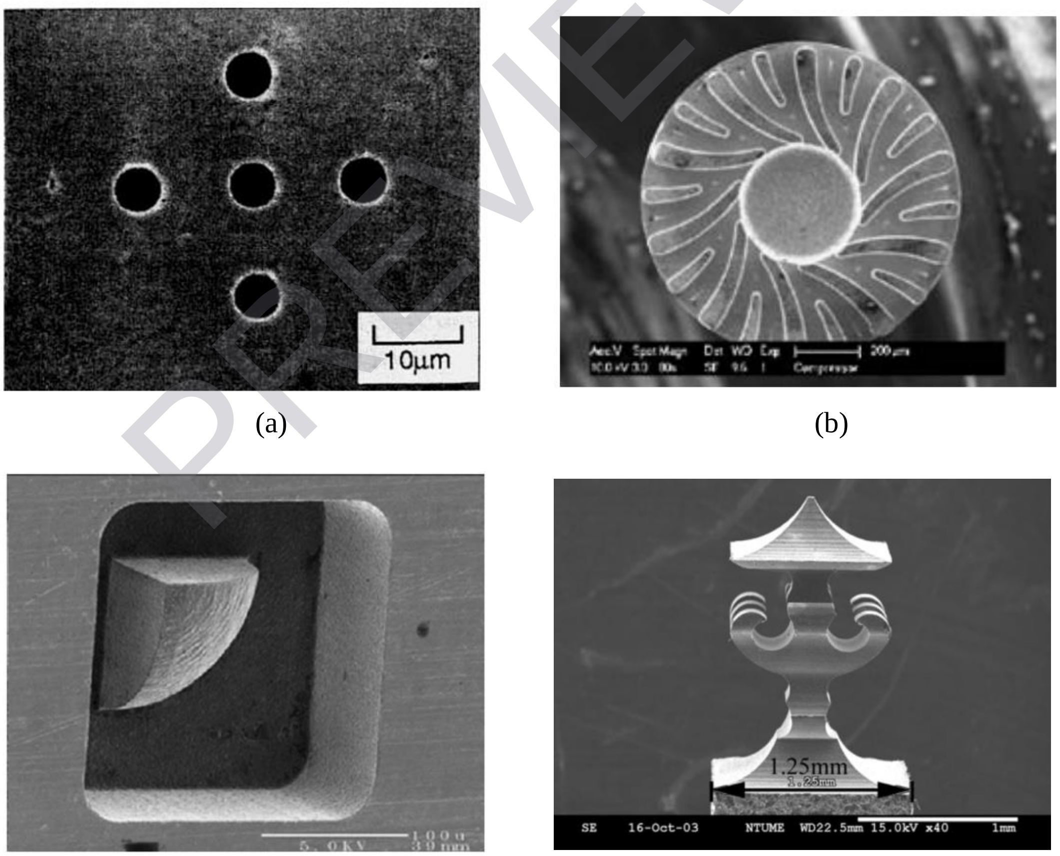


Figure 1.1 EDM process mechanism. [2]

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.



(a) (b)

(c) (d)

Figure 1.2 (a) Ø5µm 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 contradictories 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 expending 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.