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ANALYSIS OF MICRO-SCALE EDM

By

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ABSTRACT

Micro electromechanical systems (MEMS) are presented and the application of electro discharge machining (EDM) to this scale of manufacture is discussed. A model relating input variables to output variables of micro scale EDM is developed using dimensionless groups and least squares regression. The model is used in a numeric simulation that ultimately predicts the space of a micro crater. Experimental validation is performed to check the reliability of the model by comparing the measurable experimental outputs with the outputs predicted by the model. The results and validity of the model are discussed.
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1. INTRODUCTION

1.1 RESEARCH OBJECTIVES

Micro electromechanical systems (MEMS) are having a profound affect on industry as well as society. One of the objectives of this research is to investigate MEMS and to determine how an existing technology can be used as a manufacturing technique in this exciting field of development.

The primary objective of this research is to propose a model for the EDM process when the electrode diameter is comparable to the mean discharge diameter. Several process models for EDM have been proposed. These models are focused on analytically describing the EDM process that takes place when the electrode is much larger than the mean discharge diameter.

The application of the process model is intended for micro electromechanical systems. The sizes of the electrodes used in the development of the model are within the range of the present micro machines. Since EDM can be used in micro manufacture, a model of the process at the micro level is necessary to predict the final product after the machining process.

The result of the research is a model that relates several input variables to outputs. There are numerous variables, which are combined into dimensionless groups in order simplify
the complexity of the model. A statistical technique (least squares regression) is then used to relate certain groups. The outputs are then calculated using these relationships.

The second objective of the process is to use the model in a simulation of the process. The output of the simulation is a thermogram showing the temperature distribution through a work piece as a function of time during a single spark. The simulation also calculates the shape of the crater that results of a single discharge process.

The third objective of the research is to validate the proposed model. Once the model is established using empirical data, it is used to predict outputs for certain input variables. These same inputs are used in an actual discharge and are compared to the simulated results. The difference between two results is a measure of the performance, accuracy and applicability of the model.

1.2 MICRO ELECTROMECHANICAL SYSTEMS

The last 50 years have seen incredible developments in microsystems. This development, driven by the growth of information technology, has changed modern society considerably. The invention of the transistor in 1947 led to the development of integrated circuits (IC’s) that, today, form the basis of nearly every electronic good available to consumers. There is a technological revolution that will have the same, if not greater, impact in the first half of the twenty-first century: Microelectromechanical Systems (MEMS).
Microelectromechanical Systems (MEMS) are microscopic machines and components such as valves, pumps, switches and actuators. These devices are fabricated from silicon and other materials using production methods similar to those employed by the semiconductor industry to create computer integrated circuits or "chips." But unlike computer chips, MEMS perform mechanical or optical functions in addition to electrical functions. MEMS may have moving parts, and complex optical switches and conduits. Examples of MEMS devices include inkjet printer heads, automotive air bag actuators, high-resolution digital image projectors, pressure sensors, strain gauges, biosensors, and "lab-on-chip" devices.

MEMS have found a commercial basis in the sensor industry. Medical sensors are sold in their millions and automotive sensors are sold in their tens of millions per year. This market maturity and the recent development of several new fabrication methods, MEMS research has enjoyed an explosive growth. This growth is evident in the introduction of several new journals dedicated to MEMS, more than a dozen regular MEMS conferences worldwide, and a dramatic increase in government and industrial funding for MEMS research in the U.S., Japan, and Europe.

1.3 SENSORY APPLICATIONS OF MEMS

The automobile industry provides a large market for small and cheap accelerometers that are used as part airbags in automobile safety systems. MEMS have probably influenced the accelerometer industry more than any other [1].
The accelerometers are made from surface-micro machined polysilicon. A center mass allows for sensitivity in one direction by suspending it using support beams. The acceleration of the sensor causes deflection of the support beams. The resulting strain causes a measurable change in resistance in the diffused piezoresistive traces in the support beams.

Some manufacturers still produce accelerometers using advanced non-micromachine techniques but the market is shifting toward micromachines for the reduction in cost and size.

Figure 1.) Bulk-micromachined accelerometer (Courtesy of EG&G IC Sensors)

Bulk micromachined pressure sensors form the largest portion of MEMS produced worldwide. These pressure sensors are especially useful in the medical industry. The drop in price of micromachined blood pressure sensors meant that it has become cheaper to
replace the sensors than to maintain them. This has increased their sales and usage to the
degree where they are today used disposably.

![Silicon Micromachined Pressure Sensors](image)

**Figure 2.** Bulk-micromachined sensor capable of measuring differential
(Courtesy of EG&G IC Sensors)

Similar to accelerometers some of the pressure gauges measure the resistance change of
piezoresistive traces as one surface of the device is deflected by a pressure difference
across it. Others measure the change in capacitance between a membrane and a second
parallel plate.

MEMS have also found an application in strain measurement. Micro strain gages have
been developed which are several orders of magnitude smaller than those that are
presently commercially available.
MEMS have great potential as an application in chemistry. One day, tabletop mass spectrometers, gas chromatographs, and electrophoretic separation systems could be replaced by “lab-on-chips” that can analyze minute quantities of chemical quickly and accurately.

Figure 3.) *Micro machined channels, reagent reservoirs (circular), and testing chambers (hexagonal) on a "lab-chip." (Courtesy of Caliper Technologies)*

The underlying principle behind these “lab on chips” is electrophoresis. Electrophoresis is the process of chemical analysis by measuring the behaviour of chemical constituents (ions) when an electric field is applied to them. Larger ions move more slowly than smaller ones and many groups have shown the use of anisotropically etched channels in silicon can be used for chemical separation and analysis. Because of the minute quantities of specimens used the analysis time is only a few seconds.

By measuring the angular velocity of a body and integrating it over time it is possible the measure the angular position of the body. This is the basis for the operation of most
modern day gyroscopes. A common angular sensor design utilizes the Coriolis effect to couple the driven vibration of turning forks to the secondary vibration that is proportional to the rate of rotation [2][3][4].

1.4 OPTICAL APPLICATIONS OF MEMS

Atomic force and scanning tunneling microscope (AFM and STM) tips are almost exclusively micromachined. Micromachining is the only practical way to achieve the sharp tips and weak suspensions required in AFM.

Figure 4.) Silicon nitride beam for AFM (Courtesy of Park Scientific Instruments)

Micro screens have been developed that consist of large arrays of digitally controlled mirrors on a single silicon chip. The applications of these screens include projection displays and 600 dots-per-inch colour printers.
Optics is another industry that is going to be hugely influenced by MEMS technology. This specific area is undergoing intensive research with an eye on producing low-cost, low power wireless devices. Many optical MEMS have micro-hinged plates as integral structures[5]. One such machine is the corner cube reflector[6] that is used to encode a binary optical data stream.

Fresnel mirrors can be made by strategically patterning rotated polysilicon plates.[6] The lens can be held vertically and are then used to form complete optical benches on a single chip.

![Micro-Fresnel lens coupled to a diode laser (Courtesy of M.C. Wu)](image)

**Figure 5.** Micro-Fresnel lens coupled to a diode laser (Courtesy of M.C. Wu)

### 1.5 ROBOTIC AND AEROSPACE APPLICATIONS OF MEMS

Work is underway at Jet Propulsion Laboratory, the Aerospace Corporation and companies in Germany to develop micro satellites. These satellites will perform the same functions as conventional satellites, except instead of weighing a few hundred kilograms
they will weigh only a few kilograms. This has huge advantages when considering the saving in payload that needs to be launched into space.

The use of micro fabrication techniques in the manufacturing of mechanical parts has lead to the realization of micro robots. The building blocks of these robots are micro sized links, joints, coupling and motors[8].

1.6 MEDICAL APPLICATIONS OF MEMS

MEMS are even reaching into the realm of biomedicine. One experiment uses MEMS to measure the contractile force of a single cardiac cell[9]. The cell is glued between two polysilicon clamps. When the cell contracts the clamp supports deflect. The spring constant of the supports is known and the deflection is measured, hence, contractile force can be measured. The microstructures have a tiny mass and a large bandwidth. This makes it possible to make measurements at a cellular level.

There is also a chip that can connect an onboard microprocessor to the brain in order measure the brains electrical signals[10].
1.7 MANUFACTURING METHODS

There are four basic methods of manufacture:

LIGA (Lithographie, Galvanoformung, Abformung (German))

The LIGA process exposes PMMA (polymethyl methacrylate) plastic with synchrotron radiation through a mask. Exposed PMMA is then washed away, leaving vertical wall structures. Metal is then plated into the structure, replacing the PMMA that was washed away. This metal piece can become the final part, or can be used as an injection mold for parts made out of a variety of plastics. Structures a third of a millimeter high and many millimeters on a side are accurate to a few tenths of a micron.

Silicon Surface Micro machining

Silicon surface micro machining uses the same equipment and processes as the electronics semiconductor industry. This technique deposits layers of sacrificial and structural material on the surface of a silicon wafer. As each layer is deposited it is patterned, leaving material only where the designer wishes. When the sacrificial material is removed, completely formed and assembled mechanical devices are left.
Silicon Bulk Micro machining

A number of structures can be made using the etch stop planes in crystalline silicon.

EDM, Electro Discharge Machining

Electro Discharge Machining has the capability to make very small, precise parts out of almost any material that conducts electricity.

1.8 PROBLEMS ASSOCIATED WITH MEMS

Although there is much optimism and many good predictions have been made concerning the development and applications of MEMS, many have as yet failed to come true[11]. The main reason for this is that mankind is not physically adapted to deal with objects that are so small[2]. Even the existing mechanisms used for handling conventional microelectronics are not suited to the handling of the even more sensitive MEMS. Tactile inspection might be several orders of magnitude too large for the manufacture of a micro system.

During fabrication three phases can be recognized: Bulk fabrication, chip fabrication and handling that is associated with the assembly of the micro machine. Bulk fabrication refers to the manufacture of the mechanical components of the system e.g. mass, supporting beams, gears etc. Chip fabrication is the making of the electronic components
that is done in a similar fashion to the manufacture of microelectronics. The handling phase is the last phase in which the components are assembled and, if necessary, placed in their packaging. The bulk fabrication and handling aspect poses the most serious problems in the manufacture of MEMS.

Micro sensors are dictated to by the minimum displacement or rate the sensing method can measure. The smallest displacement that can be sensed is limited by the space available in the MEMS system. This can be explained by the use of an example: piezoelectric sensors. A piezoelectric material is a material that can generate an electrical charge when subject to mechanical strain or, conversely, can change shape when subjected to voltage[12]. The charge is amplified and the signal can be calibrated to measure the change in size the material has undergone during the stressing process. The magnitude of this voltage is dependent on the initial size of the crystal and is given by[13]:

\[ V_o = G h \sigma \]
\[ = \frac{E}{2(1+\nu)} h \sigma \]
\[ = \frac{E^2}{2(1+\nu)} h s \]
\[ = \frac{E^2 h}{2(1+\nu)} \Delta l \]

where

- \( G \) is the shear modulus of elasticity
- \( \nu \) is Poisson’s ratio
- \( E \) is Young’s modulus
\( h \) is the thickness of the crystal
\( l \) is the original length of the crystal
\( s \) is the strain of the crystal under loading
\( \Delta l \) is the change in crystal length

The output of the detection and amplifying stages of the sensor always contains a certain amount of noise (thermal in the case of electronic amplifiers). The output signal from the piezoelectric material needs to greater than this noise in order for it to have any meaning. This minimum output requirement forces a compromise between the minimal displacement detection and the minimum size that the sensor can be made. If the manufacturing process fixes the size of the sensor, this, in turn, limits the displacement detection. Rate sensors (accelerometers and gyroscopes) are also limited by this size constraint since the acceleration is ultimately measured as a function of some structural deflection in the micro system.

One way of solving this problem is to use sensing techniques that have smaller minimal displacements. Amongst these optical systems have the most favourable criteria for being used in MEMS. The following table shows a comparison between various methods of detection.
Table 1.) Comparison between five sensing methods[2].

<table>
<thead>
<tr>
<th>Sensing Method</th>
<th>MDS [nm]</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitive</td>
<td>4.3</td>
<td>Applicable on chip</td>
<td>Cross talk with drive</td>
</tr>
<tr>
<td>Piezoresistive</td>
<td>0.2</td>
<td>Applicable on chip</td>
<td>Needs CMOS compatible fabrication methods</td>
</tr>
<tr>
<td>Optical Sensing</td>
<td></td>
<td>No cross talk with drive Integrative</td>
<td>Needs internal illumination Lower sensitivity</td>
</tr>
<tr>
<td>Differential in CMOS</td>
<td>0.15</td>
<td>Standard Silicon Integrative</td>
<td>Complex to integrate</td>
</tr>
<tr>
<td>Differential</td>
<td>0.05</td>
<td>Geometrical linear gain</td>
<td>Complex to integrate</td>
</tr>
<tr>
<td>Beam Deflection</td>
<td>0.004</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The tolerances in conventional machining can be several orders of magnitude smaller than the desired part size. The desired size of micro machines is often smaller than the tolerance associated with conventional machining. The need for extremely small machining error is a substantial problem in micro machining. This means that micro machining is precision machining.

This need for precision machining means that the identification and minimization or correction of errors generation factors is very important. Micro machining involving machine tools has several error generation factors. The most common ones are mechanical deformation, thermal deformation, surface integrity, gap between tool and work piece and coordinate shift in tool handling.
Mechanical deformation is a common problem in micro machining using conventional machining techniques like milling, drilling etc. The tools or work pieces used in micro machining tend to be very slim and small forces lead to deflections that are large in proportion to the size of the final product. For instance, consider a micro tool used in a micro lathe. The micro tools can be modeled as a cantilever with a point load being exerted on the one end. Lets say the tool has cross sectional dimensions of 50 \( \mu \text{m} \) by 50 \( \mu \text{m} \) and a length of 1mm from the tool holder. The maximum deflection of the tool is 5\( \mu \text{m} \). The maximum deflection of the tool is given by[14]:

\[
y_{\text{max}} = \frac{FL^3}{3EI}
\]

The force that causes this deflection is

\[
F = -\frac{3y_{\text{max}}EI}{l^3}
= -\frac{3(5 \times 10^{-6})(207 \times 10^9)(50 \times 10^{-6})^4}{12(1 \times 10^{-3})}
= 1.6 \times 10^{-9} \text{N}
\]

This force is tiny on any scale. Some of the implications of this are as follows:

a) The rate of machining is slow since material removal rate limited to reduce the deflection of the tool.

b) The work piece material has to be chosen so that its material properties meet the limitations set by the machining process.

c) The application of lathing in this instance is not viable and an alternative nontraditional machining method needs to be used.
Thermal deformation is a proportional to the size of work pieces and/or tools. It is thus of lesser importance in MEMS.

Surface Integrity is an important factor. It should be in proportion to the size of the machined features. A surface finish of $R_a = 3\mu m$ is consider to be a good surface finish in conventional machining. However, $3\mu m$ could exceed the size of the part made in micro machining.

The tools produced in some dedicated electrode manufacturing system and transferred to the machine meant for micro machining, will result in errors due to clamping or chucking as shown in figure below. This serious problem is called co-ordinate shift.

![Diagram of tool errors in micro machining](image)

**Figure 6.** Tool errors in micro machining

Deformation and damage of the tools can occur during the transportation to the micro-EDM machine. The best solution for solving such errors in transformation of coordinate information is on-the-machine tool making[15]. In this system the table coordinates are
common for the tool making process and micro machining. Consequently the highest accuracy is expected.

Coordinate shift problems are encountered when assembling micro parts. When a micro machined part is dismantled from the machine and put in a box, it will lose its coordinate information. So there is a great difficulty in assembling such micro parts. Again the solution will be on-the-machine assembly.

1.9 ELECTRODISCHARGE MACHINING

Electrical discharge machining (EDM) is a nontraditional metal removal process[16]. It utilizes electrical breakdown of a fluid dielectric to remove small amounts of material due to localized heating in the vicinity of the discharge.

There are many theories concerning the operating principles involved in the EDM process. The basic requirements needed for an EDM process are:

a) A work piece that is made of a conductive material
b) A conductive electrode
c) A dielectric that lies between the work piece and the electrode
d) A voltage source
e) A means of controlling the current (either active or passive)
The fundamentals of an EDM system

From a macroscopic perspective the EDM process occurs in the following way. The electrode is brought close to the work piece leaving a small gap between them. A potential is applied between the electrode and the work piece that sets up an electric field within the dielectric. This field is increased to the point where it is greater that the breakdown field strength of the dielectric. At this point the dielectric breaks down and an electrical discharge occurs. Current begins flow, causing heating in the vicinity of the discharge. Heating of the work piece causes melting and evaporation of the material in the form of a crater on the surface of the work piece. The current is then turned off so that an arc is not formed. The process is then repeated.
1.9.1 A DETAILED EXAMINATION OF THE EDM PROCESS

The explanation of the EDM process in the previous section is a considerable simplification of the process used to relate the various components involved. Electrical discharge machining is a very complex process, many of whose phenomena are not fully understood. Several theories have been presented attempting to explain the principles associated with the process. Amongst these, three more predominate theories are available[16]:

**The electro mechanical model.**
This model states that the material removal is performed by intense electric fields that overcome the cohesive forces in the crystal lattice adjacent to the surface of the work piece. This theory is not well supported by experimental evidence and is not generally accepted.

**The thermo mechanical model.**
This model proposes “flame jets” erode material by means of heat transfer to the surface of the work piece. The model excludes the electrical characteristics associated with the current flow in the process and attributes the heat generation to various phenomena associated with the electric breakdown of the dielectric. The theory does not agree with the experimental evidence and is not a good explanation of the EDM process.
The thermo electrical model.

This is the best explanation of the EDM process although it does not entirely explain all the phenomena associated with this type of machining. The model centers on the theory that high temperatures and temperature gradients are generated during a discharge due the large current densities produced during the discharge.

The EDM process, described using the thermo electrical model, works in the following way. The electrode and work piece are brought close together. They are insulated from each other by a fluid dielectric (e.g. air, oil, dematerialized water).

![Figure 8. Polarization of the dielectric](image)

A potential is applied between the work piece and the electrode. This potential is measured as a voltage applied across the dielectric. This voltage is increased, setting up an increasing electric field between the electrode and the work piece in the dielectric. The dielectric polarizes and positive and negative streamers are formed. At this value of the applied voltage the electric field in the dielectric becomes larger than the electric field strength of the dielectric material and the material starts to ionize[17]. The ionization occurs where the electric field is greatest between the electrode and work piece. Small
irregularities (asperites) cause field concentrations that catalyze the initiation of the discharge.

Figure 9.) **Discharge and the formation of vapour bubble**

A current starts to flow through the electrode, the dielectric, and the work piece. A channel is formed out of partially ionized gas that conducts the current by means of ions and electrons. Due to the intense current densities, heating of the dielectric produces a vapour bubble. The heating of this vapour bubble causes it to expand thus reducing the current density of the conducting channel.

Figure 10.) **Material removal**
The current flows into the work piece through a very small cross-sectional area. This means that a large heat flux is being applied at the surface of the material causing excessive heating in the vicinity of the discharge. This heating causes the melting and vaporization of the work piece in the form of a crater. Molten material is ejected by means of a shock wave generated by the process.

![Diagram of the EDM process](image)

**Figure 11.) Cycle end**

The potential between the electrode and the work piece is removed after a certain time and the current ceases to flow, the heating of the vapour bubbles stops and it collapses. The partially ionized gas recombines and the dielectric acts as an insulator again.

1.9.2 CHANNEL EXPANSION

The conducting channel through which energy is passed to the work piece is a focal point of the EDM process. The behaviour of this channel ultimately determines the performance of the machining process[18][19]. An understanding of the plasma channel and its behaviour is fundamental to the understanding of the details of the EDM process. The expansion of the channel determines many of the end product phenomena observed in EDM. The channel expansion is explained as follows:
When the dielectric begins to ionize the electrons and ions are exposed to an electric field that is present between the electrode and the work piece. The electrons and ion particles have, respectively, net negative and net positive charges associated with them. When exposed to the field they are accelerated in opposite directions, electrons to the anode and ions to the cathode. The electrons have much less mass than the ions and are thus accelerated much faster than the ions. The electrons also cause an avalanche effect by striking molecules and knocking electrons off them. This effect is similar to the Zener effect in solid-state electronics. The result is a high-density current passing through the dielectric in the form of a plasma channel.

This current causes heating of the plasma channel. This heating causes the dielectric to heat up to the extent that it vapourizes and forms a gas bubble around the channel. Only a small amount of the conducting channel is plasma, the rest is vapour. As the channel temperature increases, the vapour bubble expands. Its rate of expansion is found by balancing the pressure and inertial forces acting on the fluid that is being displaced by the superheated vapour. The rate of this expansion has several implications on the EDM process.

The rate of channel expansion determines the rate of change of current density applied to the surface of the work piece. The current density determines the heat flux applied to the work piece. The heat flux determines the amount of material removed by and the shape of the crater resulting form a single discharge. Initially, the area cross sectional of the
discharge is small and, thus, the energy density is high. The surface of the work piece is heated above its melting point and the molten material is ejected. As the duration of the discharge continues, so the conducting channel radius increases. The area through which the current is passing, increases and the work piece surface is not heated as intensely. The metal removal rate is diminished. A stage is reached where the energy is so thinly distributed that the surface of the work piece cannot be sufficiently heated and the metal removal process stops.

The expansion rate also influences the shape of the craters formed in the work piece. The intensity of the heat flux initially means that the metal removal takes place predominately in a direction that is perpendicular to the surface of the work piece. As the discharge duration increases, the channel widens and a greater surface area parallel to the work piece surface is exposed to the heat source. The crater is increasingly eroded in the radial direction. The increasing diameter of the plasma channel and the decreasing energy intensity combine to produce craters that are shallow with a depth to diameter ratio of less than 10%.

Secondly, the rate at which the plasma channel collapses is also important. For effective machining to be done discharges must be distributed evenly over the electrode. If the discharge occurs at the same position on the work piece with too much regularity, excessive tool wear occurs and the process becomes inefficient. This kind repetitive discharging can be generated by not allowing enough time for the conducting channel to collapse entirely and for all the ions and electrons to recombine. The rate at which the
plasma channel recombines thus limits the frequency at which pulse can be applied to the electrode.

The plasma channel duration also has an effect on the tool wear ratio[20][21]. The tool wear ratio is defined as

\[
TWR = \frac{\text{Amount of material removed from electrode}}{\text{Amount of material removed from workpiece}}
\]

The moment at which maximum amount of material is removed from the work piece is not the same as when the maximum amount of material is removed from the tool electrode. If the work piece material removal is maximized, the current supplied to the electrode needs to be stopped as soon as that point where the maximum amount of work piece is removed. Further expansion of the channel will only favour the removal of tool material that is detrimental to the tool wear ratio. Should the converse be true viz. the optimum point for the work piece occurs after that for the tool, the plasma discharge duration needs to be extended to maximize the amount of material removed from the work piece.

Several approaches have been used to develop the time-heat source diameter functions[22][23]. These include

a) The thermodynamic model

The plasma channel is modeled as small cylinder that is a few microns in diameter in which a small proportion of the plasma energy is dissipated. The plasma is heated so that the channel obeys the thermodynamic laws of an ideal gas. The rate at which the channel expands is found by balancing the forces
generated by the pressure associated with the increase in temperature and the inertial forces of the dielectric surrounding the discharge.

b) The constant surface temperature model

The expansion of the channel is limited by the decrease in temperature and electrical conductivity that are caused by the cooling effect of the relatively cold electrode surface. A minimum core temperature in the plasma channel is maintained by thus limiting the rate of channel expansion. The melting temperature of the electrode determines the upper bound of the temperature scale. This value is taken in preference to the vapourization temperature because the heat corresponding to that temperature is roughly 20 times that of the melting heat.

c) Crater shape control

Experimental evidence shows that the depth to diameter ratio of the craters usually averages around 5%. In order to maintain these values the heat source needs to be increased in size in a certain fashion.

The behaviour of the plasma channel can also be modeled using the following form[24]:

\[
r_X(t_a, t) = \begin{cases} 
  a + bt, & 0 \leq t \leq t_a \\
  r_X(t_a, t) + c(t - t_a) & t_a < t \leq 2t_a 
\end{cases}
\]
$r_K$ is the plasma channel radius. For $0 \leq t \leq t_a$ power is being supplied to the channel and it is expanding. While for $t_a < t \leq 2t_a$ the channel is decreasing in size since the current has been stopped.

The current striking the surface of the work piece has a current density as follows

$$S_e = \begin{cases} \frac{m_i t}{\pi (a + bt)^2} & 0 \leq t \leq t_a \\ \frac{m_i (2t_a - t)}{\pi ((a + bt) + c(t - t_a))^2} & t_a < t \leq 2t_a \end{cases}$$

Here the function of time is broken into two pieces because of the boundary between the when the current is turned on and when the current is turned off.

Yet another model for the channel expansion is given by:

$$r_K = \sqrt{t}, \quad 0 \leq t \leq t_a$$

$r_K$ is the radius of the plasma in μm, $t_a$ is pulse on-time in μs and $t$ is time in ps.

1.9.3 THERMAL MODEL

Thermally the erosion process model starts with the heat diffusion equation. In cylindrical coordinates it can be written as follows.

$$\frac{1}{\alpha} \frac{\partial \theta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \theta}{\partial r} \right) + \frac{\partial^2 \theta}{\partial z^2}$$
where $\mathcal{G} = T - T_0$

the initial condition is as follows:

$\mathcal{G}(r, z, 0) = 0$

The boundary conditions are as follows:

$$-\lambda \frac{\partial \mathcal{G}}{\partial z} = q_0(t), \quad 0 \leq r \leq r_0(t)$$

and

$$-\lambda \frac{\partial \mathcal{G}}{\partial z} = 0, \quad r > r_0(t)$$

with

$\mathcal{G} = 0, \quad r > r_0(t)$

It is assumed that

$r_0 = r_0$

the heat flux is given by

$q_0 = \eta u_e S_e$

where $0 < \eta < 1$
$u_e$ is the voltage that appears across the spark gap. Since not all the power measured in the spark gap is used in the metal removal process a scaling factor, $\eta$, is introduced. The value used in previous work is 0.12. This means that only 12% of the power supplied to the process is used to remove metal.

### 1.10 MICRO EDM

The dimensional range in which micro EDM can be used is shown in Figure 12.

---

**Figure 12.) Dimension range of micro EDM**

Micro EDM fills the gap between conventional machining and optical lithography. The electrode size is between 5 and 100 μm. It can achieve dimensions that are too small for conventional machining processes and too large for optical processes.

Micro electrodischarge machining has ability to machine any conductive material irrespective of their mechanical hardness[25]. This ability of machining only conductive
and semi-conductive materials is a disadvantage of the EDM process[26]. Micro-EDM can process materials such as silicon and ferrite, which have high specific resistance and have the problem of cracking when processed by ordinary EDM process. Silicon is a very attractive material because of its good mechanical and electrical properties as well as its abundance and low cost. This semiconductor material, which is very popular in the electronics industry, is difficult to machine using ordinary processing technology. The ability of micro-EDM to simplify the machining of silicon makes it useful in the manufacture of micro mechatronic systems.

Micro-EDM systems are designed to maintain a gap between the tool and the work piece in order to ensure electric-discharge between them. Therefore, machining of material can be done without applying pressure on the material, including high precision machining on curved surfaces[27], inclined surfaces and very thin sheet materials which are difficult to drill. Micro-EDM is applied to minute curved surfaces to form super fine nozzles like those used for fuel injection in diesel engines and to do the high precision metal masking for printing used in the electronic device manufacturing processes. Moreover, since micro parts actually used in micro machines are extremely small, non-contact machining is particularly very important for them.

Micro EDM is essentially a surface process[28][29][30]. However, high aspect ratio machining can be done using the process. Deep micro holes have been drilled using micro EDM[33][32]. Holes 80 µm in diameter with a length of 2000µm have been produced. This application has proved to be viable in the realm of optics where it serves
as means of interfacing fibre optic cables. In an ordinary perforating process, micro-EDM can easily perforate a hole to a depth equivalent to five times the bore diameter. Electro-discharge machining has been used mainly for the machine processing of micro-molds and micro-dies used to produce micro machines. Die strength is demanded together with minute details, for dies to be used for deformation processing such as blanking of machine parts, therefore processing with aspect ratio of 5 to 10 is necessary.

High precision and high quality machining can be done. Under ideal conditions it is possible to set the roughness of the machined surface at 0.1mm R\text{max}, by minimizing the electrical energy to an infinitesimal amount. The shape of the tool electrode, its traveling locus and the electro-discharge gap determines precision of the machined shape. Moreover, the micro-EDM produces very small burrs, much smaller than those seen in mechanical drilling and milling operations and therefore does not need subsequent deburring operations.
2. PROCESS MODEL

2.1 DIMENSIONLESS GROUPS

There are several variables involved in the micro EDM model. In order to simplify the representation of the model it is decided to use dimensionless groups as part of the model. Dimensionless groups have an important role to play in the model and their principles are discussed in this section.

The principle of dimensionless groups

The units attached to physical quantities characterize each of them. If a group of these quantities is multiplied together so that their combined dimension is unity, the group is called a dimensionless group.

Dimensional homogeneity is the principle that states all the terms in an equation that is derived to represent a physical situation must have the same dimensional representation. An important application of this principle is dimensional analysis that involves the grouping of system variables, while the relationships between the system variables are not known. Products of dimensionless groups are themselves dimensionless.
Buckingham's $\pi$ theorem

The number of independent dimensionless groups that may be employed to describe a phenomenon known to involve \( n \) variables is equal to the number \( n-r \), where \( r \) is usually the number of basic dimensions needed to express the variables dimensionally.

This theorem is useful in determining which combinations of variables in a model can be grouped together to form dimensionless groups.

Method for determining dimensionless groups

Matrix manipulation is the preferred method of determining dimensionless groups. Once the variables in the model have been chosen and their units are known a dimensional matrix can to be constructed. The matrix columns signify the variables used in the model and the rows represent the power of the base dimensions used in the units of the specific variable. For example take a model as follows:

\[
F = f(a, x, m)
\]

where \( F \) is force has units mass-length per time per time per time (\( ML/T^2 \))

\( a \) is acceleration with units length per time per time (\( L/T^2 \))

\( x \) is distance with unit of length (\( L \))

The dimensional matrix looks like this:
\[
\begin{array}{cccc}
m & a & x & F \\
M & 1 & 0 & 0 & 1 \\
L & 0 & 1 & 1 & 1 \\
T & 0 & -2 & 0 & -2 \\
\end{array}
\]
is the dimensional matrix.

The correct value for \( r \) in Buckingham’s \( \pi \) theorem may now be stated as the rank of the dimensional matrix. The rank of the dimensional matrix in this example is \( r = 3 \). Thus, one dimensionless group can be obtained using these variables. Not all these variables will necessarily be used in the dimensionless groups though.

Upon reducing the above dimensional matrix the following is found:

\[
\begin{bmatrix}
1 & 0 & 0 & 1 \\
0 & 1 & 0 & 1 \\
0 & 0 & 1 & 0 \\
\end{bmatrix}
\]

The negative values of the last column are taken to be the powers of the variables used in the dimensionless groups. The original intention was to relate variables to the force \( F \) in the form of a dimensionless group. Therefore the following can be written

\[
\pi = \frac{F}{ma}
\]

As is seen, although the Buckingham \( \pi \) theorem predicted one dimensionless group using the variables, however, \( x \) is not included in the dimensionless group.
Dimensionless groups software

Software was developed in order to find the dimensionless groups from the variables used in the micro EDM model. The software used all the combinations of the model variables to output a text file that contained the variables that can be used in as dimensionless groups. The variables can then selected and the dimensionless group can be calculated.

2.2 LEAST SQUARE REGRESSION

As part of the micro EDM process a method of relating the system inputs to the dimensionless groups is needed. A set of functions (polynomials) would be preferable as these would be easiest to use in determining the input-output relationship of the model. The method of linear least square regression is proposed as a way of performing the task.

This portion of the model is critical to its success. The principle behind regression is simple, however, it can be misused. Methods of describing how well the functions fit the data need to be used in order to ascertain the effectiveness of the model. This section describes the principles least squares regression and the methods used to describe its effectiveness. It also provides an example of how regression is used in the micro EDM model.

Consider a set of data points with the coordinates \((X_1,Y_1), (X_2,Y_2), \ldots, (X_n,Y_n)\). There is an equation that predicts the position of \((X_1,Y_1), (X_2,Y_2), \ldots, (X_n,Y_n)\) as follows

\[
\hat{Y} = b_0 + b_1X
\]
For a set of $n$ observations $(X_1, Y_1), (X_2, Y_2), \ldots, (X_n, Y_n)$ we can write

$$\hat{Y}_i = b_0 + b_1 X_i + \varepsilon_i$$

such that the sum of squares of deviation from the true line is

$$S = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n} (Y_i - b_0 - b_1 X_i)^2$$

The principle of least squares is to choose $b_0$ and $b_1$ such that the value of $S$ is minimized. This is done by differentiating the above equations with respect to $b_0$ and $b_1$ and then setting the results equal to zero.

$$\frac{\partial S}{\partial b_0} = -2 \sum_{i=1}^{n} (Y_i - b_0 - b_1 X_i)$$

$$\frac{\partial S}{\partial b_1} = -2 \sum_{i=1}^{n} X_i(Y_i - b_0 - b_1 X_i)$$

The estimates for $b_0$ and $b_1$ found as follows

$$\sum_{i=1}^{n} (Y_i - b_0 - b_1 X_i) = 0$$
\[ \sum_{i=1}^{n} X_i (Y_i - b_0 - b_1 X_i) = 0 \]

by expanding and rewriting the set of normal equations are found

\[ b_0 n + b_1 \sum_{i=1}^{n} X_i = \sum_{i=1}^{n} Y_i \]

\[ b_0 \sum_{i=1}^{n} X_i + b_1 \sum_{i=1}^{n} X_i^2 = \sum_{i=1}^{n} X_i Y_i \]

writing these in matrix form

\[
\begin{bmatrix}
  n & \sum_{i=1}^{n} X_i \\
  \sum_{i=1}^{n} X_i & \sum_{i=1}^{n} X_i^2
\end{bmatrix}
\begin{bmatrix}
  b_0 \\
  b_1
\end{bmatrix}
= 
\begin{bmatrix}
  \sum_{i=1}^{n} Y_i \\
  \sum_{i=1}^{n} X_i Y_i
\end{bmatrix}
\]

or

\[
X'X = \begin{bmatrix}
1 & 1 & \cdots & 1 \\
X_1 & X_2 & \cdots & X_n \\
1 & \cdots & 1
\end{bmatrix}
\begin{bmatrix}
1 & X_1 \\
1 & X_2 \\
\vdots & \vdots \\
1 & X_n
\end{bmatrix}
= 
\begin{bmatrix}
  n & \sum_{i=1}^{n} X_i \\
  \sum_{i=1}^{n} X_i & \sum_{i=1}^{n} X_i^2
\end{bmatrix}
\]
\[ X'Y = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ X_1 & X_2 & \cdots & X_n \end{bmatrix} \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} Y_i \\ \sum_{i=1}^{n} X_i Y_i \end{bmatrix} \]

therefore

\[ X'Xb = X'Y \]

solving for \( b \)

\[ b = (X'X)^{-1}X'Y \]

This is the general form of the normal equation used in least square regression.

**Analysis of variance.**

An analysis of variance shows how well the regression polynomial models the measured data. Figure 13 shows the variable needed for this.
Figure 13. Geometry of least square regression

From Figure 13

\[ \sum (y_i - \bar{y})^2 = \sum (\hat{y}_i - \bar{y})^2 + \sum (y_i - \hat{y}_i)^2 \]

which is explained as follows:

(Sum of squares about the mean) = (sum of squares due to regression) + (sum of squares about regression.)

It can be shown that the mean of the predicted values of \( Y \) is the same as the mean of the original data points. The sum of squares about the mean is due to the variation of the data about its mean. The sum of squares due to regression is due to the variation of the predicted values around the mean. The sum of squares about regression is due to the variation of the predicted values about the actual values in the data.
From the above definitions it is seen that the smaller the sum of squares about regression
the closer the predicted value of Y approximate the actual values. If one takes the ratio:

$$R^2 = \frac{\text{SS due to regression}}{\text{SS about mean}}$$

then an indication of how good the regression is, is how close the value of $R^2$ is to one.

2.3 MICRO EDM MODEL

![Process model diagram](image-url)

*Figure 14.* Process model
The proposed micro EDM process model takes system input variables and relates them to outputs. The model thus represents and describes the system that lies between the electrode and the work piece. The model applies from the initiation of the discharge until the power to the process is stopped by the controlling electronics.

2.3.1 Measurable Inputs.

Spark gap voltage ($V_{gap}$)
This is the potential that exists between the electrode and work piece during a discharge. This voltage is chosen because it is a characteristic of the discharge process. It is different to the applied voltage in that the applied voltage is independent of what is happening during the discharge. The applied voltage appears across the switching electronics and since the model is focused on the discharge behaviour it is decided to use the gap voltage since it is a better indication of the process.

Applied current ($I_a$)
The applied current is current that flows through the discharge. Since the discharge and switching transistor are in series the current is measured through a small series resistor. The same current flows through the discharge, switching transistor and series resistor.

Spark duration ($t_s$)
The spark duration is the length of time during which current is flowing through a discharge.
Electrode diameter ($d$)

Cylindrical electrodes were used in the construction of the model mainly due to their availability in the diameters of interest. The electrode diameter is the cross sectional diameter of the electrode.

Permittivity of the dielectric ($\varepsilon$)

Air was used as the dielectric between the electrode and work piece. It was taken to have a relative permittivity of 1 and thus the permittivity of the dielectric is $8.85 \times 10^{12}$ F/m.

Electric field breakdown strength ($E_d$)

The electric field strength is the field at which the dielectric begins to ionize. The breakdown strength of air was taken to be 1MV/m.

2.3.2 MEASURABLE OUTPUTS.

Crater area ($A_c$)

This is the area of the crater that is left after a discharge. It is a measure of how much material is removed during the discharge.

2.3.3 NON MEASURABLE PARAMETERS

Velocity of channel ($v_r$)

The radius of the conducting channel increases during the discharge process. The rate at which this occurs is the channel velocity. It is not physically possible to measure this
velocity. Because of the small magnitude of the channel diameter and the limited amount of time during which the channel exists conventional measurement techniques are not feasible to perform such measurements. Even modern capacitance coupled devices (CCDs) that can sample a 1Mfps (1 000 000 frames per second) are incapable of providing the desired resolution needed for such measurements.

The channel velocity is thus measured on a quasi-static basis. The pulse duration is controlled and the channel area is measured. The resulting crater area is modeled as a circle and the diameter is calculated. The change in diameter for each pulse duration is obtained and the difference between them is calculated. The difference is divided by the difference in pulse length to give the average channel expansion velocity during the discharge.

*Current density during discharge (Jc)*

The current density is the applied current divided by the crater area. It is a measure of the current intensity.

To actually measure the amount of charge (number of electrons) passing through the conducting channel is impossible. However, the current flowing into the electrode is known and the channel area is obtainable using the area of the crater. The current density can be obtained in a similar manner to that used to obtain the channel expansion velocity.
Power dissipated across gap \((P_{ch})\)

The power dissipated is measured by multiplying the gap voltage by the applied current.

A Watt meter to measure the power dissipated through the plasma channel would need a response not yet achievable in those devices. The gap voltage and applied current are measurable. By multiplying these two quantities the power dissipated in the channel is calculable.

The power thus includes both the power dissipated in the channel as well as the power used to remove material. Ideally it would be desirable to measure these two components independently. Practically it is not possible to place a probe in the conducting channel to measure the power dissipated in the channel.
2.3.4 System Definition

The system is chosen as shown in Figure 15. The energy input is provided electrically by applying a voltage above the series resistor. The energy is supplied by a parallel capacitor and the stored energy is given by:

\[ E = \frac{1}{2}(C + C')V^2 \]  

[33]
\( C = \text{capacitance of the capacitor (pF)} \)

\( C' = \text{stray capacitance (pF)} \)

\( V = \text{applied voltage (V)} \)

Some of the applied energy is dissipated through the series resistor and the resistance intrinsic in the switching mechanism used to control the discharge duration. The focus of the process model is the discharge and not the system as a whole. The discharge lies between points 1 and 2. In order to measure the energy associated with the discharge the assumption that all the components of the system are in series and thus the current flowing in the series resistor and the discharge is the same. By then measuring the voltage across the discharge, the power, and hence the energy consumed, dissipated through it can be calculated.

How this energy is divided up between the different processes occurring during the discharge is not the emphasis of this process model. It is noted that energy is divided between the polarization and ionization of the dielectric, the heating of the dielectric and work piece and the expulsion of material from a machined crater. The model is aimed at a larger scale in which the total energy consumed during a discharge is correlated to the amount of material removed during the discharge.

There are 12 system variables. To reduce the number of variable combinations a number of relevant dimensionless groups have been derived and are used to relate measurable inputs to measurable or derivable outputs.
2.3.5 Behaviour of Dimensionless Groups.

The dimensionless groups are multivariable functions. From an experimental perspective the values of the \( \pi \) are determined by varying one input while keeping the other constant. In so doing, a function can be determined that describes the \( \pi \) number as a function of that variable. The process can be repeated for all the groups' variables.

The problem is that when the dimensionless groups are used in an input-output relation they need to be combined into a single number that characterizes the system at the value of all the input variables. In order to do this a function needs to be determined that represents the combination of the \( \pi \) group functions that are single variable functions of the isolated variables.

For example.

\[
\pi_1(t_g) = \frac{I_d t_g}{V_{pop} d e}
\]

is the function of \( \pi_1 \) with the discharge time as the independent variable.

The same thing can be done for the other variables giving the functions: \( \pi_1(I_a) \), \( \pi_1(V_{pop}) \), \( \pi_1(d) \) and \( \pi_1(e) \).

When using them in the input-output relationship the combination of all \( \pi_1 \) functions are to be used. In order to get this combination multiple variable least square regression is used.
2.3.6 INPUT VARIABLES

The input variables (except $E_d$) are grouped into a dimensionless group $\pi_1$.

$$\pi_1 = \frac{I_0 t_s}{V_{gap} d_c}$$

The output variables are found in the following dimensionless groups:

The output dimensionless groups are expressed in terms of $\pi_1$ using least squares regression. Experimentation was done using the input variables and the outputs were recorded. The variables were combined into dimensionless groups.

$\pi_1$ was used as the independent variable (X). A set of dimensionless groups was developed that incorporate the output variables. These groups are used as the dependent variables (Y). The method of least squares is then used to relate X to Y. The following functions giving these relationships are shown under the headings of the output variables they are used to determine.

2.3.7 RELATIONSHIPS BETWEEN $\pi_1$ AND $\pi_2, \pi_3, \pi_4, \pi_5$
\[ \pi_2 = \frac{V_a^2 e^2}{I_{ds}^2 J_e} \]

**Figure 16.** Measured and approximated plots of \( \pi_2 \) vs \( \pi_1 \)

\[ \pi_2 = e^{-55.68} \left( \pi_1^{1.3849} \right) \]
\[ \pi_3 = \frac{d^2}{A_c} \]

\[ \pi_3 = e^{55.6854 \left( \frac{1}{\pi_1} \right)^{-2.8539}} \]

Figure 17. Measured and approximated plots of \( \pi_3 \) vs \( \pi_1 \)
\[ \pi_4 = \frac{P_{ch}}{A_c R_e J_e} \]

Figure 18.) *Measured and approximated plots of \( \pi_4 \) vs \( \pi_1 \)

\[ \pi_4 = e^{3.2693} (\pi_1 - 0.264) \]
\[ \pi_5 = \frac{I_e^2 v_f^2}{I_a} \]

\[ \pi_5 = e^{-38.52 (\pi_1^{1.6277})} \]

**Figure 19.** Measured and approximated plots of \( \pi_5 \) vs \( \pi_1 \)
3. SIMULATION

3.1 PLASMA CHANNEL SIMULATION

In order to simulate the thermal characteristics of the micro EDM process it is necessary to know the heat flux that is being applied to the surface of the work piece. This heat flux originates from the plasma channel that exists between the electrode and the work piece. The model presented in section 2 has the rate at which the plasma channel is expanding as one of its outputs. This is used to calculate the channel radius as a function of time.

The simulation is done in the following way:

a) The electrode diameter, relative permeability, and breakdown field strength of the dielectric are fixed at the beginning of the simulation.

b) The initial values of spark gap voltage, and the discharge current are entered into the simulation.

c) The dimensionless group, \( \pi_1 \), is calculated.

d) Using the functions found using the method of least squares regression a value for \( \pi_5 \) is found.

e) The channel velocity is found by using the equation defining \( \pi_5 \).

f) The incremental change in channel diameter is found by assuming the calculated value of \( v_r \) is the average value across the time interval. The displacement is found by multiplying \( v_r \) by the time increment.
g) The channel diameter is found by adding this increment to the previous channel diameter.

The flux intensity is assumed to be constant across the channel and is found in a similar fashion to that of the channel diameter as follows:

a) \( \pi_1 \), calculated from the input conditions used to calculate the channel diameter, is used to calculate values for \( \pi_3 \) and \( \pi_4 \).

b) Values for the channel area and the channel power, \( A_e \) and \( P_{ch} \), are calculated from \( \pi_3 \) and \( \pi_4 \).

c) The flux intensity is found by dividing \( P_{ch} \) by \( A_e \).

\[ \text{Figure 20.) Flowchart of plasma channel simulation} \]
3.2 THERMAL SIMULATION

The dissipation of electrical energy as heat is one of the principle mechanisms used to perform material removal during the EDM process. The transfer of this heat from the surface of the work piece is of considerable interest since it determines how the material is removed. As part of the investigation into the behaviour of the EDM process under micro conditions a simulation of the heat transfer was performed. This section documents the theory, approach used for and results attained from the simulation.

3.2.1 THEORY

The theory used for the simulation is based on the heat diffusion equation. The general form is given by:

$$\frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) + \dot{q} = \rho c_v \frac{\partial T}{\partial t}$$

It is difficult to attain an analytical solution for a two or three-dimensional case. It is somewhat easier to rather solve the equation numerically using either a finite difference or finite elements method.

3.2.2 SIMULATION APPROACH

The method of finite differences is used to solve the heat diffusion equation and simulate the heat transfer during the discharge process[34]. The two underlying equations used in this method are as follows:
\[
T_{m,n+1} + T_{m,n-1} + T_{m+1,n} + T_{m-1,n} - 4T_{m,n} = 0
\]

\[
T_{m,n+1} + T_{m,n-1} + 2T_{m-1,n} + \frac{2q'' \Delta x}{k} - 4T_{m,n} = 0
\]

The subscripts used apply to different nodes as shown in figure 21.

**Figure 21.) Node Convention**

Certain assumptions are made that limit the extent to which the finite difference solution models the actual heat transfer process. These assumptions are listed as follows:

a) The above equations are valid only if \( \Delta x = \Delta y \) thus the area under investigation is always square.

b) The thermal conductivity \((k)\) is assumed to be constant and uniform throughout the temperature range of the simulation.

c) The work piece is assumed to be at a uniform temperature before the heat flux applied.

d) The surfaces that are not exposed to the heat flux are assumed to remain at a constant temperature.
3.2.3 FINITE DIFFERENCE ALGORITHM

The source code for the solving of the heat transfer equations is included on the accompanying. A flow diagram shows its operation.

\[ \text{Calculate the temperature of the center node using the four other nodes.} \]

*Figure 22.*) Flow chart of *findif* function
Initialize the number of nodes and iterations

Set the minimum number of nodes to 3

Calculate the present number of nodes

Set the present number of nodes to the absolute minimum

Are the present number of nodes less than the desired number of nodes?

Increase present nodes by 2N-1

Calculate the new number of X nodes and the new Y dimension

End

Figure 23.) Flowchart of the nodes function
Set the number of frames

Specify the size of the square

Call the nodes function

Specify the surface temperatures of the block

Specify the magnitudes of the heat flux

Set the thermal conductivity of the work piece

Are all the frames complete?

Is this the first run?

Y

N

Calculate heat flux on each node of the top surface using normal pdf

Initialize surface temperatures

Calculate the temperature of each surface node with incident heat flux

Initialize positional information

Load temperatures with the values for the calculation of central node temperature

Call first function

Set toggle to true

Have all the node temperatures been calculated?

Y

N

Load node temperatures with oblique values

Load node temperatures with rectilinear values

Call init

Set toggle to true

Update current position

Call contour function

Save contour frame to disk

End

Figure 24.) Flowchart of heatflow function
Matlab® 6.1 by Mathworks, Inc. was used as the software package to compile the algorithms developed. The code is fully commented explaining how it functions.

### 3.3 Simulation Results - Plasma Channel Aspect

#### 3.3.1 Current Density

\[ J_e = \frac{V_a^2 e^2}{\pi_2^2 \alpha_s^2} \]

*Figure 25.* Plot of \( \pi_2 \) vs \( \pi_1 \)
The current density begins at a high value when the channel diameter is smaller. It decreases to a steady state whose magnitude is determined by the amount of current applied to the process.

3.3.2 CHANNEL AREA

\[ A_e = \frac{d^2}{\pi} \]
Figure 27.) Plot of $\pi_3$ vs $\pi_1$

Figure 28.) Channel Area

The channel area increases from zero to a constant value. The relative size of the final crater is determined by the amount of voltage appearing across the spark gap.
3.3.3 POWER DISSIPATED IN CHANNEL

\[ P_{ch} = A^2 R_e J e \pi \]

Figure 29) Plot of \( \pi_4 \) vs \( \pi_1 \)

Figure 30) Power dissipated in channel

The power dissipated decreases during the discharge
3.3.4 CHANNEL EXPANSION VELOCITY

\[ v_r = \frac{\pi_5 I_0}{\sqrt{\pi_s^2 J_c}} \]

*Figure 31.* Plot of \( \pi_5 \) vs \( \pi_1 \)
Figure 32. Channel expansion velocity

The channel expansion velocity starts off at a high velocity when the heat intensity inside the channel is high. The velocity will tend to decrease toward 0 m/s as the process continues.

3.4 SIMULATION - THERMAL ASPECT

Simulations were performed for different input conditions and were plotted using contour maps. Maps for each time interval were stored and then played back showing the change in temperature distribution as a function of time as well as the predicted temperatures occurring during the micro EDM process. The simulation showed the characteristic crater shape that is associated with the EDM process. A sample of these contour maps is shown in the following graphic.
Figure 33.) *Temperature distribution through work piece*
3.5 VALIDATION RESULT COMPARED TO SIMULATED RESULTS

Figure 34.) Measured and model values of current density as a function of pulse duration

The measured current densities decrease with increasing pulse duration. Since the channel diameter and the channel resistance increase with time these results agree with theory. There is much variation in the current density for pulse duration less than 500ns. This is because of the difficulty in maintaining a fully formed conductive channel during such a short interval. The model provides results that are larger than the measured values. The large variations demonstrated by the measured data are not present in the model values since the least squares regression has an averaging effect.
The channel area increases with time. This also agrees with theory since the heat generated by the discharge forces the conducting channel to expand. The model predicts values that are smaller than the measured values. This explains why the values for the current density are elevated with respect to the measured ones: the current density is inversely proportional to the area. If the channel under evaluated then the current density is over estimated. The shortcoming of the model is due to function chosen during the regression process. The function is not responsive enough to deal with the rapid changes in crater area.
Large amounts of power are dissipated in the first 500 ns of the discharge process. The conducting channel is compact. The electron density along with the avalanche effect leads to a high current resulting in a correspondingly high power output. As the discharge continues to take place, the channel resistance increases and the power dissipation decreases. The model gives power values that are somewhat larger than the measured values.
Figure 37.) Measured and model value of channel velocity as a function of pulse duration

The measured values of the rate of channel expansion are fairly representative of the values measured by other researchers. The rate of expansion decreases with increasing pulse duration. This is consistent with what is expected. As the discharge expands and cools the pressure decreases and the rate at which channel expansions decreases. The model exaggerates the velocities at the beginning and end of the discharge them toward the end. Between 2000ns and 8000ns the model behaves fairly well, giving good predictions of the channel velocity.
4. EXPERIMENTAL

4.1 EXPERIMENTAL SETUP

4.1.1 APPARATUS

The basic equipment needed for the experiment is as follows:

a) A test rig that can position the electrode relative to the work piece in such a way that the electrode can be moved axially towards the work piece.

b) A power supply

c) A switching circuit to control the power applied during the process.

d) An oscilloscope used to measure the voltage waveforms associated with each discharge.

e) An electrode

f) A work piece

4.1.2 THE TEST RIG

Figure 38.) The test rig.
The bottom layer provides a base for the rest of the rig. It also forms a point of attachment for the voltage source. It is made of conductive material so that workspace can rest placed against it and automatically be connected to the supply circuit. The bottom layer has glass fiber strips glued around the edges of its upper surface that act as insulation between the bottom layer and the top layer. The bottom layer is mounted on an X-Y table and moves with the table. The X-Y table is moved in either direction by turning a micrometer style screw attached to each direction of travel. It is electrically isolated from the X-Y table.

The top layer is used to carry the tool holder. It also acts as an electrical point of attachment for the ground terminal. The top layer is mounted in such a way that it is stationary. The X-Y table and hence the bottom layer moves relative to the top layer in the X direction. If the X-direction screw is turned the work piece is either moved horizontally towards or away from the electrode.
The electrode holder consists of two metal strips that are bolted together with the electrode trapped between them. The holder is designed to fit into the top layer in such a way that they do not slip in the X-direction. The tool holder is also used in the preparation of the electrodes.

4.1.3 Power Supplies

Three separate power supplies were used as part of the apparatus.

a) The process power supply (0-110V). This provides the power necessary for the EDM process. It is connected in parallel to a bank of high-speed (WIMA) capacitors. The power supply charges the capacitors and discharge gets its power from them. The capacitors obtained have a much faster response time than the power supply and simulate an ideal voltage source.

b) The small signal power supply (±5V, ±12V). This supply is used to supply the switching electronics such as the operational amplifiers (used as comparators), buffers, inverters, and D-latches.

c) The transistor gate power supply (14V). The voltage at which the EDM process operates made it necessary to use a third power supply that provides a high enough voltage to drive the main current transistor into saturation.

4.1.4 Switching Circuit


The in order to perform the experimentation a circuit is needed to control the current flow. This circuit has to have the following requirements[37][38]:

b) the circuit has to allow for a single discharge.

c) the duration of the discharge need to be controlled to a preset length of time.

d) the input voltage and current need to variable.

The single spark requirement leads to the choice of the electronically based circuit. The reasoning behind this is as follows. A square pulse is desired for the experimentation purposes. This pulse has an on duration 250 ns and 10 μs. In order to ensure that the discharge exists only for the desired amount of time the switching mechanism needs to be triggered automatically by the initiation of the spark. It was decided to design an electronically based circuit since it provides a better control of the current than that offered by a RC relaxation circuit.
Figure 40.) **Switching circuit**

Figure 10 shows the switching circuit. A supply voltage is connected to a resistor in series with the electrode. This resistor limits the amount of current that is allowed to flow through the discharge and protects the switching transistor. This transistor is placed in series with the electrode and is used to stop the flow of current to the discharge. A connection between the drain of the transistor and a comparator monitors the voltage just above the transistor. The output of the comparator is fed into an inverting comparator (The output is 180° out of phase with the input). From the comparator the signal passes...
through a series of inverters. There are an odd number of inverters so that a rising edge on the input of the inverters is inverted at the output. This signal is connected to the gate of a transistor used as part of a delay circuit. A capacitor is connected between the drain and the source of the transistor. The source of this transistor connected to a 5V source via a resistor. A connection is made from between the resistor and the capacitor to a comparator. From the comparator the signal goes to the clock input of a D-latch. The output of this D-latch is connected to the clock input of another D-latch. The output of the second D-latch is connected to a non-inverting comparator. The signal from this comparator passes through a buffer to the gate of the main switching transistor thus completing a closed loop system.

4.1.5 SWITCHING CIRCUIT OPERATION

The switching circuit operates as a closed loop that automatically controls the current flowing through the discharge[38].

The initial conditions, prior to a discharge, are as follows:

a) The gate on the current switching transistor is high and the transistor is hard on (in saturation).

b) Since no current is flowing in the discharge the voltage measured just above it is equal to the preset supply voltage.

c) The gate of the transistor in the delay circuit is high and thus the transistor is on. The output from just above the capacitor is low since the drain and the source are essentially short circuited by virtue of the fact that this transistor is on.
d) The first D-latch after the delay circuitry is initialized to have a low output.
e) The second D-latch is initialized to be high. This single is transmitted via a comparator and buffer and hence gives the initial condition in a)

When the electrode is brought near enough to the work piece the field strength becomes large enough for the dielectric to break down between the electrode and the work piece. A discharge occurs and the voltage of the electrode drops since the discharge causes the impedance of the dielectric to drop. The first comparator monitors this voltage drop and when it drops below a certain level the output of this comparator changes from low to high. This signal is then transmitted through 11 inverters. The inverters are used to provide a time delay by virtue of their propagation times. The odd number of inverters means that output signal is the complement of the input signal.
Figure 41.) Time delay sub system

The output of the inverters is connected to the gate of a transistor that is part of a time delay system. The transistor is initially on thus current flows through it and the series resistor. The drain voltage is approximately equal to the source voltage that is attached to ground. When the gate signal goes from high to low the transistor turns off and the capacitor is switched in series with the resistor. The capacitor voltage is governed by the equation

\[ v = V_o - I_o R \text{e}^{-\frac{t}{RC}} \]

The time taken to charge the capacitor acts as a delay. The output from the delay subsystem is fed into a comparator that provides a rising clock signal for a D-latch. The D-latch is originally loaded with a low signal and is clocked high. The output of this latch is used for a clock signal for a D-latch that is initialized with a high output. The latch is clocked low and thereby turns the gate of the current switching transistor off. It does this via a comparator and buffer.

4.1.6 Oscilloscope

In order to measure the electrical characteristics of the micro EDM process an electrical oscilloscope was used. Two channels were used and were connected as follows:

Channel 1: The probe is connected to anode (work piece). The reference is connected to the supply.

Channel 2: The probe is connected to cathode (electrode). The reference is connected to the supply.
Since the references of both channels are connected to a voltage that is not at the same potential as ground it was necessary to remove the ground from the oscilloscope to prevent a short circuit. The measurements were then taken relative to the supply voltage.

The oscilloscope used is a digital scope. It thus has a finite resolution of 8 bits or 256 discrete levels. This means that using an accuracy of 0.41V can be achieved using a supply voltage of 110V. This is one of the practical limitations of the experimentation.

4.1.7 ELECTRODE

Cylindrical electrodes were used having diameters 40, 60 and 120μm. The electrode material is copper. The electrode is clamped between the holders to hold it in position. The holders are rest on the top layer of the test rig. The top layer is connected to ground. The electrode is thus the cathode.

4.1.8 WORK PIECE

The work piece is a block of aluminium that is polished on one side. The polished side is used as the surface on which the discharge takes place. The work piece rests on the bottom layer of the test rig that is connected to the voltage source. The work piece is the cathode.

4.2 TESTING

4.2.1 PREPARATION OF WORK PIECE AND ELECTRODE.
Since micro EDM produces minute surface phenomena it is necessary to have a smooth electrode and work piece surface. Thus the first task in performing the testing was to prepare both the work piece and electrodes. The surface preparation was performed by polishing the work pieces. The surface roughness value ($R_a$) for EDM is between 5 and 10 μm. This value of $R_a$ ranges from about 2 to 5 μm for polishing. Thus, by using a polished work piece it is possible to measure the surface phenomena created during a single pulse EDM process.

The work piece surface was polished using a fine polishing agent and a rotating polishing disk. The electrodes were first cut to the desired length and then placed between two pieces of adhesive tape. The adhesive tape was used just to make handling of the electrodes easier. The electrodes were then placed in an electrode holder with a short length protruding from the gap between its two halves of the holder. This end was polished using the same technique used for the work piece. The ends of the electrodes were polished until they were flush with the end of the tool holder. An effort was made to ensure that the ends of the electrodes were perpendicular to the end of the tool holder so that an electrode with flat perpendicular end could be achieved.

4.2.2 THE TESTING PROCEDURE
Two electrode holders and work pieces were used in the testing procedure. One set contained the actual test specimens and the other set was used for calibration purposes.

The experimental procedure was as follows:

a) The electrode holder containing the calibration electrode is placed on the tool holder along with the calibration work piece.

b) The applied voltage is set to the desired level.

c) The reference voltage on the triggering comparator is set to a level just below that measured on the electrode (the electrode voltage is scaled using a voltage divider). The reference voltage is adjusted using a potentiometer.

d) A test using the calibration electrode and work piece is performed to make sure the current control is operating. Turning the X-axis dial of the X-Y table moves the work piece closer to the electrode until a discharge occurs.

e) Operations c) and d) is repeated until the current triggering works satisfactorily.

f) The pulse length is then set by one of three methods:

i. The capacitance between the drain and the source of the delay transistor can be varied.

ii. The delay subsystem comparator voltage reference can be set.

iii. One or more pairs of the inverters can be switched in or out of the circuit

The methods above are listed in increasing order of resolution. The capacitance variation is used when large delay adjustments are needed \( (t_{\text{delay}} > 5 \mu s) \). The comparator voltage is used for a range of \( 250 \text{ ns} < t_{\text{delay}} < 5 \mu s \). The finest
resolution is given by the propagation times of the inverters \((t_{\text{prop}} = 6\,\text{ns})\). The pulse duration can be set to an accuracy of 12 ns.

g) Calibration tests are performed to set the pulse duration. The pulse duration is measured on the oscilloscope.

h) Once the current triggering and pulse duration are set the calibration electrode and work piece are replaced with test specimens.

i) A test is performed in the same way that which was performed using the calibration equipment.

j) Once the discharge is completed the electrode is removed from its holder and is stored. The position of the discharge on the work piece is also noted.

k) The traces measured on the oscilloscope are stored.

4.2.3 ELECTRO MICROSCOPY

The work pieces were marked prior to each test by dividing the polished surface into squares running horizontally across the block (6 squares per block). Each block is approximately 3mm by 4mm. Prior to the commencement of a discharge the block was positioned so that the electrode was central to a new block.

In some of the cases (those with the higher supply voltage) a mark on the surface of the work piece was visible after the discharge. A permanent marker was used to circle these marks to facilitate the electro microscopy that occurred after the tests were completed. Those squares that had no visible crater markings were left untouched.
The samples were then placed in an electron microscope. It was found that under low magnification a darkened region on the surface of the work piece signified the presence of a crater. The microscope was then zoomed in on that region in order to obtain a higher resolution image of the crater.

4.3 EXPERIMENTAL RESULTS

The results are found as follows:

Table 2.) Experimental Results (Electrode diameter = 40\(\mu\)m)

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Table 4.) Experimental Results (Electrode diameter = 120μm)

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</tr>
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</table>
The craters formed by the discharge were viewed under an electron microscope. A few examples are shown in the figures below.

![Micro crater: \(V_{\text{gap}}=9.94\text{V}, I_s=4.05\text{A}, t_s=250\text{ns}\) ](image)

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Current</th>
<th>Gap</th>
<th>Power</th>
<th>Duty Cycle</th>
<th>Impulse Duration</th>
<th>Crater Size</th>
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<td>10000</td>
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</tbody>
</table>
Figure 43. Micro crater: $V_{\text{gap}} = 11.83\, \text{V}$, $I_a = 4.1\, \text{A}$, $t_s = 500\, \text{ns}$
Figure 44. **Micro crater:** $V_{gap}=14.10V$, $I_a=4.1A$, $t_s=5000ns$
5. CONCLUSIONS

Conventional EDM models do not incorporate the effect of electrode size. The size of the electrode is so large when compared to the width of the conducting channel that it is not considered having an effect on the discharge process. Some models ignore the electrode completely and use an ideal flux source as the point of departure for the rest of the analysis. The model presented here does include the electrode diameter as one of its inputs. As the electrode width decreases it becomes comparable in dimension to the diameter of the plasma channel. The present model incorporates the effect of this physicality and extends the range over which the process can be predicted.

The discharges produced in convectional EDM are distributed over a large area when compared the area affected by the individual discharges. The micro EDM model deals with a single spark that occurs from a single point. If multiple discharges were produced they would be forced to occur at the same position on the electrode. This property is useful in MEMS where precision is essential. The micro EDM model is based on this situation that is different to those model emulating conventional EDM.

The micro EDM micro is also based on the precise delivery of energy to process. Convectional EDM sets input current and the frequency of pulses to maximize the MRR. It is not concerned with controlling the amount of each discharge since the amount of material removed by individual discharges is almost negligible when compared to the
total removed when the machining is completed. The micro EDM process is much more sensitive to the material removed by individual discharges. The model, being based on single discharges, establishes a means of predicting the micro effects of EDM for differing inputs.

The primary objective of the research was to develop a process model that provides an analytical relationship between the process inputs and the process outputs. This objective was achieved. However, the effectiveness of the model is open to some debate. Although the model follows the trends of the process, it only provides accurate results over a certain range of input values. The reasons for this are described in the following paragraphs.

The EDM process tends to be somewhat of an uncertain process. Even in large scale EDM, there is no guarantee that every discharge is going to provide the desired material removal. The best one can hope for is that, given the right input parameters, the system will respond in such a way as to remove the desired material. Factors like dielectric debris (contaminants), work piece material inhomogeneity and surface finish play an important part in whether a discharge will occur in the desired position or even occur at all. This difficulty is overcome by having many discharges (up to 500 kcps in some cases) and then taking the average material removal as the criterion for the determining the effectiveness and efficiency of the process.
In the case of micro EDM process the luxury of having many discharges to play with is not available. The amount of material removed by a single discharge has a significant impact on the geometry of the end product. Every discharge is thus significant. The ability to predict and control a discharge thus becomes more important as the size of the work piece decreases. The better one can control a single discharge, the smaller the work piece can become. The miniaturization of components and the work pieces that they are made from is the goal of MEMS.

The control of the electrode is also a problem in the experimental process. Alignment of the electrode is a problem meaning that not every discharge occurred under the same geometric conditions. This has an effect on the electric field generated in the dielectric that determines when and where (distance from work piece) a discharge occurs. More care should be taken in positioning and aligning the electrode relative to the work piece.

The difficulty in proposing a model using these single discharges is how to determine which discharge is representative of the process and which is an aberrant “misfire”. From the experimentation done in this research it was decided that if there was current flow during the entire on-time of the transistor then the discharge was a success and added to the data used to generate the model. Even this approach is not full proof since there are instances where current did flow during the on-time of the transistor but no crater could be found as evidence of material removal. These occurrences are associated with short circuits between the electrode and work piece.
The data generated by successful discharges has a huge range. This makes the use of least squares regression unreliable. Least square regression was chosen as the method of relating the π because it provided a means of giving analytical formulae. In hindsight it is not the best method for doing this. Least squares regression provides a function that minimizes the average error between the function and the data it is meant to represent. The large range of the experimental data means that this function shows the trend of the data but there is a large discrepancy between the approximated and measured values (small $R^2$ values). This insufficiency can be seen in the simulation results. The functions do not contain much information about what happen to the process outside the bounds of the experimental input values except perhaps the trend in which the process is tending.

There better methods of attaining the relationships between dimensionless groups among these are cubic splines and the weighted sums of neural networks. It is, however, difficult to derive analytical functions using these methods.

The current controlling system worked really well. The response times and amount of current overshoot were kept to a minimum. The reasons for the good current switching are, firstly, the use of high-speed electronics and secondly the minimization of inductance in circuitry. The decreased inductance kept the system as close to a single order system as possible reducing the response overshoot. 110A/μs and settling time of around 20ns were attained.
The forgoing results were attained using feedback that leads to the conclusion that for a micro EDM process to be effective feedback needs to be used. Not only in the electrical control but also in the positioning and alignment of the electrode. From a model perspective, feedback should also be used to map the input variables to the outputs. Back propagation neural networks can be useful tools in this regard.
APPENDIX A. REFERENCES


[33] Eubank, P.T., Patel, M.R., Barrufet, M.E, Bozkurt, B., "Theoretical models of the electrical discharge machining process. II the variable mass, cylindrical plasma model. Journal of Applied Physics 73(11); 7900-7909, June 1993


