Study of novel micro EDM using foil electrodes

Meenakshi Sundaram Murali

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Study of Novel Micro EDM Using Foil Electrodes

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A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
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2006

To my father

Abstract

Micro electro discharge machining (micro EDM) is a non-traditional process used for the micromachining of electrically conductive materials, especially hard metals. The principle applications of micro EDM are in hole making and micro groove machining. When compared to micro hole making, the amount of material removal (and hence, the tool wear) is much higher in the case of micro groove machining. This requires frequent tool re-grinding or tool electrode changing. Hence, a novel micro groove machining technique, which can ensure long hours of unattended machining, is highly desirable.

A novel micro groove machining technique by micro electro discharge machining, using microfoils as tool electrode (FAST EDM) is proposed in this research. Using this new process, micro grooves having width less than 40 μm and depth more than 50 μm have been machined. The length of the micro grooves are 25 mm. This new technique has the advantage of micromachining continuously for long hours (weeks) without electrode re-grinding. Tungsten, stainless steel and graphite foils have been used as tool electrodes to machine micro grooves in tool steel (XW 42).

To improve the performance of this process, two novel flushing techniques, namely Gavity Assisted Micro EDM (GAME) and magnetic field assisted micro EDM, were invented. The first technique makes use of the gravitational forces in debris removal. In this method the workpiece is clamped to the spindle and the tool electrode is held in the work table. Spark erosion takes place beneath the workpiece. The debris formed falls into the dielectric tank and is flushed away.

The second technique is useful in the machining of ferromagnetic workmaterials. It makes use of magnetic field in the transportation of ferro magnetic debris out of sparking zone. Experimental validation reveals that these techniques can be a useful aid in high aspect ratio micromachining. Experimental study of the effect of these flushing techniques vis-à-vis tool electrode materials is presented in this thesis. The material removal rate by graphite tool electrode is found to be 30 to 40 times higher than the material removal rate achieved by tungsten and stainless steel tool electrodes. A maximum material removal rate of about 530 $\mu\text{m/hr}$ is achieved by graphite in GAME. Among the tool electrodes considered, tungsten provides the minimum surface roughness. An arithmetic average surface roughness (R_a) of 0.3 μm is obtained by using a tungsten electrode.

Numerical studies using the finite element method, were conducted using commercially available software (ANSYS 7 University High) to study the thermal effect of the micro EDM process on titanium alloy (Ti6Al 4V) workmaterial. Atomic force microscopy and nanoindentation techniques were used for the experimental verification of simulated results and it is found that the thermal stress induced by the micro EDM process is less than about 300 MPa.

The novel technologies proposed in this research work are especially useful in the unattended machining of high aspect ratio micro grooves and have the potential for the application of micromachining of metallic components, such as micro heat exchangers and particle separators.

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List of Multi-media files

(Available in CD ROM)

1. good machining.wmv
2. micro needle formation.wmv
3. sacrificial machining.wmv

List of Abbreviations

AFM	atomic force microscope
BEDMM	brush electro discharge mechanical machining
CAM	computer aided manufacturing
CNC	computer numerical control
EDM	electro discharge machining
EWR	electrode wear rate
FAST EDM	foil as tool in EDM
FEM	finite element method
GAME	gravity assisted micro EDM
MRR	material removal rate
MST	micro system technology
RLC	resistance-inductance-capacitance
RPM	revolutions per minute
SEM	scanning electron microscope
UR	unit removal
WEDG	wire electro discharge grinding

Nomenclature

d_{of}	penetration depth of the bulk material (m)
d_{f*}	penetration depth of the crater zone (m)
d_{te}	diameter of tool electrode (m)
h	convective heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
k	distribution parameter
l_g	length of the groove (m)
l_f	length of the foil electrode (m)
l_m	total workpiece movement (m)
m	mass (kg)
$\{m\}$	thermal strain vector
q	uniform heat flux density rate (W m^{-2})
q_{max}	maximum heat flux density rate (at $r = 0$) in Gaussian distribution (W m^{-2})
q_r	varying heat flux density rate at a radial distance r in Gaussian distribution (W m^{-2})
r	radial distance (m)
r_s	spark radius (m)
t	time (s)
t_{on}	spark <i>On-time</i> (s)
t_{sg}	spark gap (m)
$\vec{B}$	magnetic flux density / magnetic induction (T)
C	specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$)

$[C]$	specific heat matrix
C_d	capacitance (F)
$[D]$	elasticity matrix
E_0	Young's modulus of the bulk material (Pa)
E_*	Young's modulus of the crater zone (Pa)
E_d	discharge energy (J)
$\vec{F}$	resultant force (N)
$\vec{F}_B$	magnetic force (N)
$\vec{F}_C$	centrifugal force (N)
$\vec{H}$	magnetic field strength (Am^{-1})
H_0	hardness value of the bulk material (Pa)
H_*	hardness value of the crater zone (Pa)
K	thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
$[K]$	conductivity matrix
K_C	constant based on the material toughness ($\text{MPa}\cdot\text{m}^{1/2}$)
Q	total heat flow rate (J s^{-1})
$\{Q\}$	nodal heat flow vector
Q_a	heat absorption rate by anode (J s^{-1})
Q_p	heat flow rate applied as concentrated point load (J s^{-1})
Q_r	heat absorption rate by an annulus ring at a radial distance r in Gaussian distribution (J s^{-1})
R_a	average surface roughness (m)

R_z	average peak-to-valley height (m)
T	temperature (K)
$\{T\}$	vector of nodal temperatures
$\{\dot{T}\}$	vector of time derivatives of $\{T\}$
T_o	ambient temperature (K)
T_i	initial temperature (K)
$\{V\}$	velocity vector for the moving workpiece
V_d	discharge voltage (V)
W_{min}	minimum obtainable groove width (m)
α	thermal diffusivity (m^2s^{-1})
β	coefficient of thermal expansion (K^{-1})
$\{\varepsilon\}$	strain vector
η	fraction of the total heat absorbed by the anode
κ	constant of proportionality
μ	magnetic permeability (Hm^{-1})
$\vec{\mu}$	magnetic dipole moment (J T^{-1} , $\text{m}^2\text{-A}$)
v	velocity (ms^{-1})
ρ	density (kg m^{-3})
$\{\dot{\sigma}\}$	stress vector (Nm^{-2})
Γ	boundary
Ω	domain
∇	gradient operator

Chapter 1

Introduction

Micro electro discharge machining is a non-traditional process used for the micromachining of electrically conductive materials, especially hard metals. Electro discharge machining (EDM) is preferable for metal micromachining owing to its unique abilities such as

- Machining of hard materials
- Machining of fragile components
- Machining irrespective of the crystal orientation
- Burr-free machining
- Un-manned machining for long times

All these advantages of EDM can be taken for granted when applied to micromachining, except for the ability to do un-manned machining for long hours. This is due to the effect of rapid tool electrode wear, which is an inevitable part of EDM [1]. A small amount of tool wear (on the order of micrometers) which can be neglected as “part of the game” in macro EDM becomes critical in the case of micro EDM. Since the dimensions of the features made in micro EDM are in the range of micrometers, even small tool electrode wear is to be monitored and controlled in micromachining. This requires frequent human intervention (for tool re-grinding). A process development that can enable long hours of un-manned machining will enhance the status of micro EDM as a viable metal micromachining technique. The description of the micro EDM process, the motivation, objective and scope of the present work as well as the layout of the rest of the thesis are covered in this chapter.

1.1 Description of micro EDM

Micro Electrical Discharge Machining (micro EDM or μ EDM) is a technique adapted from the conventional EDM machining process for the purpose of micro machining. Material removal in micro EDM is by melting and vaporization. The working principle is the same for EDM and micro EDM [2]. However, the key difference lies in, how, in micro EDM, the discharge energy is reduced and electrode vibration is controlled [3]. In the case of micro EDM the process energy discharged per spark is precisely controlled to be on the order of 10^{-6} to 10^{-7} J [4]. Small unit removal (UR) is achieved in micro EDM by reducing discharge energy of each pulse [5]. For controlling this, the stray capacitance is kept to a minimum. The schematic configuration is shown in Figure 1.1.

Figure 1.1 A typical relaxation circuit used in micro EDM [6]

The various types of EDM processes and the shapes machinable are given in Table 1.1.

Table 1-1 Machinable shapes by EDM [7]

product	applicability, movement	electrode	type of EDM
hole ○	1 (RE)	cylinder, pipe	drilling, milling
hole □	1, 2, 3 (RE)	rod	sinking, milling
groove	2, 3, 1 (RE)	disc, plate	EDG, sinking
3D cavity	1	3D shaped	sinking
spindle ⊗	1, RW	block	EDG
rod ⊠	2	wire (backup)	WEDG
3D convex	3	wire (line)	WEDM

1, 2, 3 ----- dimension of the relative movement between electrode and workpiece
 (RE) ----- electrode with or without rotation
 RW ----- workpiece with rotation

1.2 Motivation

The principle applications of micro EDM are in hole making and micro groove machining. Three-dimensional micro EDM with simple shape electrodes is an emerging technology [8]. Micro grooves are predominant features in micro system components such as micro heat exchangers, linear actuators, ratchets, optical switches, fibre alignment devices, and particle separators. When compared to micro hole making, the amount of material removal (and hence, the tool wear) is much higher in the case of micro groove machining. This requires frequent tool re-grinding or tool electrode changing. Hence, a novel micro groove machining technique, which can ensure long hours of unattended machining, is highly desirable. This is possible if a micro foil is used as a tool instead of the traditional pin-shaped electrode. Ultra thin foils with thickness as low as 1 micrometer and less are readily available in the market. These foils can be straight away used for micro groove machining without any need for down sizing by time-consuming electro discharge wire grinding. An attempt in this direction is made in this research work.

1.3 Objective

The objectives of the research work are given below:

1. To introduce an alternate micro groove machining method using micro EDM
2. To explore high aspect ratio machining
3. To invent novel flushing techniques for effective debris removal
4. To determine the effect of novel flushing techniques on material removal rate (MRR) and surface finish
5. To study numerically the thermal effect of the process on work material and estimate the residual stress

1.4 Scope of work

In the present work a novel micro EDM process capable of very long period (weeks) of un-manned operation for the machining of microgrooves is envisaged. This is primarily done based on the experimental work using the micro EDM machine (MG-ED72W) with necessary modifications in the tool holding method to use the foil electrode. Tungsten, graphite and stainless steel foils are used as tool electrodes. Experiments are conducted on both ferrous (tool steel) and non ferrous (titanium alloy) work materials. To improve the micro EDM process, two novel flushing techniques based on the utilization of gravitational and magnetic forces in debris removal have been proposed. The work also involves numerical studies using commercially available finite element software (ANSYS) to predict the extent of thermal effect on the workmaterial. Characterization of spark eroded surfaces is done using equipment such as a confocal microscope, scanning electron microscope (SEM), atomic force microscope (AFM), laser interferometer (WYKO), optical microscope (OMIS), Talyscan, and nanoindenter.

1.5 Outline of the thesis

A critical literature review in micro electro discharge machining is presented in Chapter 2. The experimental methodology and the use of state of the art metrological instruments in the characterization of spark eroded surfaces are explained in Chapter 3. Details of a novel micro groove machining technique by micro EDM using micro foil as the tool electrode is narrated in Chapter 4. Novel flushing techniques which are applicable to micro EDM are discussed in Chapter 5. In Chapter 6, the numerical studies and process simulation conducted using commercially available finite element software (ANSYS) to study the crater shape formed by a single spark and the residual stress induced by micro EDM is explained. Finally the thesis concludes with the summary of the work done and suggestions for further research work.

Chapter 2

Literature review

This chapter reviews electro discharge machining as a micromachining technology. The discussion consists of three sections. The basics of electro discharge machining are presented in the first section that covers the history of the electro discharge machining process, EDM theory, machining types, process parameters and their influence. The technological advances made over the years and the state of the art of micro EDM technology are discussed in the second section that covers the major research issues, the theoretical, numerical and experimental studies undertaken in this field. The final section contains the summary of the outcome of the literature review.

2.1 Basics

2.1.1 History

Electro discharge machining (EDM), alias spark erosion technique, is an electro-thermal material removal process that falls under the category of unconventional manufacturing methods, as chips, in the traditional sense, produced by mechanical action, are absent in this process. EDM is capable of producing intricate shapes on any electrically conductive material irrespective of its hardness [9]. Since EDM is a non-contact process, the mechanical forces are almost absent and hence, this technique is an ideal choice for machining fragile components [10]. Materials with electrical resistivity below 300 Ω -cm are machinable by EDM [11].

The history of EDM can be traced back to the experimental works of Joseph Priestly in the 1770s [12]. However, metal erosion by spark discharges was put to constructive use only in 1940s, by the Russian couple Lazarenkos [13]. Since then tremendous progress has been made in the field of EDM. From its humble beginning as a repair tool to remove broken drills and taps [14], EDM has emerged, over the period of time, as the fourth most popular machining process [15]. The works of Prof. Masuzawa on the application of spark erosion in the arena of micromachining has paved the way for the successful emergence of micro electro discharge machining [16-20]. The recent developments and the state of the art in electro discharge machining has been reviewed by Ho and Newman [21, 22] wherein micro EDM is identified as the recent trend in spark erosion machining and an exclusive review on micro EDM has been done recently by Pham et al. [23].

2.1.2 Theory of Micro EDM

Spark erosion is a highly complex process and due to its stochastic nature it is very difficult to understand the mechanisms involved completely, even though it has commercially been used for more than half a century [24]. Among the different theories proposed such as the electro-mechanical, thermo-mechanical and thermo-electrical, the thermo-electrical theory has emerged as the widely accepted theory. It proposes the high temperature generated by the high intensity of the discharge current as the most important factor that determines the erosion of electrode material [25]. In this section, the working principle and the sequence of events in the commonly agreed material removal mechanism of micro EDM are discussed.

2.1.2.1 Working principle

The two electrodes (workpiece and tool electrode) are initially separated by a dielectric medium. Potential is applied between the electrodes and the tool electrode is gradually brought closer to the workpiece. When the gap between the two electrodes reaches a critical value, the dielectric, which is initially nonconductive, breaks down and suddenly becomes conductive and energy is discharged as spark. The sparking zone is subjected to a very high temperature as the momentary local plasma column temperature reached is estimated to be in the range of 10,000 to 60,000 K [26-28]. Experimental measurement done by Albinski et al. using spectroscopic techniques shows plasma column temperature between 8,000 to 10,000 K [29]. In the case of metals, material is removed from both workpiece and tool electrode by melting and vaporization [30-32]. In the case of conductive ceramics, which are characterized by high melting point, low thermal conductivity and high thermal expansion, the material removal is by flaking of material due to high temperature gradients – a phenomenon known as thermal spalling [33-35]. Besides these two typical material removal mechanisms, other mechanisms can occur such as oxidation and dissolution of the base material [36].

2.1.2.2 Sequence of events during spark erosion

The sequence of events leading to the electro erosion is described below and illustrated in Figure 2.1.

1. The voltage applied between the electrode and workpiece builds up an electric field throughout the space between the electrodes (See Figure 2.1 a). As a result of the power of the field and the geometrical characteristics of the surfaces, conductive particles suspended in the fluid concentrate at the point where the field is strongest. This results in a bridge being formed (See

Figure 2.1 b). At the same time electrons are emitted from the negatively charged electrode (See Figure 2.1 c). They collide with neutral particles in the space between the electrodes and split them into positively and negatively charged particles. This process spreads at an explosive rate and is known as impact ionization. This development is encouraged by bridges of conductive particles.

Figure 2.1 Sequence of events during electro discharge machining [37]. A typical sparking cycle takes about 1-4 micro seconds to complete.

2. Electrons and ions migrate to anode and cathode respectively at a very high current density. A column of vapour begins to form and localised melting of workpiece commences (See Figure 2.1 d). The discharge channel continues to expand along with a substantial increase of temperature and pressure (See Figure 2.1 e).
3. When the power is switched off, the current drops (See Figure 2.1 f); no further heat is generated, and the discharge column collapses (See Figure 2.1 g). A portion of molten metal evaporates explosively and / or is ejected away

from the electrode surface. With the sudden drop in temperature the remaining molten and vaporized metal solidifies. A tiny crater is thus generated at the surface.

4. The residual debris is flushed away along with products of decomposition of dielectric fluid (See Figure 2.1 h). The application of voltage initiates the next pulse and the cycle of events.

2.1.3 Micro EDM Types

Micro EDM can be subdivided into following categories, which are schematically shown in Figure 2.2:

- a) *Micro die-sinking* [38-40] : A process in which a tool electrode with suitable micro features is used to replicate a mirror image in the workpiece. As a result the peaks and valleys of the tool electrode are reproduced as corresponding valleys and peaks in the workpiece. Making the tool electrode with micro features and tool wear are the concerns in this technique.
- b) *Micro wire-EDM* [41-43] : A process in which a continuously moving very thin wire of diameter less than 300 μm is used as tool electrode to make ruled surfaces on the workpiece. Better accuracy is achieved in this process as fresh wire is always used as the tool. Wire breakage and pre-hole drilling are the major concerns with this technique. Moreover, this process is not suitable for machining blind features.
- c) *Micro milling* [44-46] : A process in which complex three-dimensional shapes are made in workpieces by profiling a simple pin-shaped tool electrode in a CAM generated tool path. A suitable CAM system capable of compensating the tool wear is the major requirement in this fast emerging technique.

- d) *Micro wire electro discharge grinding* [47-49] : An online tool making process invented by Prof. Masuzawa [50], in which a continuously moving wire is used to grind the tool electrode already mounted in the machine spindle. This built-in process eliminates alignment errors as manual handling of tool electrode after grinding is avoided.
- e) *Micro drilling* [51-53] : A process in which micro rods are used to make micro holes with diameter as small as 25 μm and less in the workpiece. This process is so far the most widely used micro EDM technique.

Figure 2.2 Schematic representation of micro EDM types [54]

2.1.4 Process parameters and their influence

The common behaviour of electro discharge machining is that higher discharge energy will produce higher material removal rate (MRR), tool wear and surface roughness [55-57]. Lowering the discharge energy, on the other hand, will improve the surface finish and reduce the tool wear but the MRR also will decrease. Hence, one needs to find an optimum balance based on the design requirements [58-60]. Apart from the discharge energy, several other process parameters and their effects as shown in Table 2.1 also need to be understood.

Table 2-1 EDM process parameters and their influence [61-63]

Process parameter	Influence
Spark On-time	It is the time during which machining takes place. Increasing spark On-time will produce a larger crater, higher MRR and roughness as more energy is discharged with longer spark On-time.
Spark Off-time	It is the time during which the plasma channel collapses and molten material is removed. Longer spark Off-time reduces the machining time and hence, less material is removed. Shorter spark Off-time will make the process unstable. Hence, an optimum value needs to be used.
Voltage; current	Discharge energy is proportional to these factors. Spark gap increases with voltage. Higher current produces deeper surface damage. Hence, a lower voltage and current settings are preferable for finishing.
Material	Higher MRR can be achieved on materials having lower thermal conductivity and melting temperature.
Frequency	Roughing is done at low frequency as longer spark On-time can be set. Finishing is done at higher frequency.
Polarity	For wire EDM and micro EDM it is preferable to have the tool electrode as the cathode as less tool wear is a critical requirement to avoid tool breakage.
Dielectric liquid	Liquids with higher dielectric strength, lower viscosity and specific gravity, produce less arcing and hence, are preferable for finishing operation.

Professor Rajurkar and his team at the *"Center for Non-Traditional Manufacturing Research, University of Nebraska-Lincoln"* have conducted extensive research using the commercial Panasonic MG-ED72W micro EDM machine and have identified the major process parameters and their influence. The experimental conditions used by the researchers are given in Table 2.2 and the results are shown in Figure 2.3.

Table 2-2 Micro EDM Experimental Conditions [64]

Pulse generator	Relaxation type
Open circuit voltage	70, 80, 100 (V)
Capacitor	3300, 220, 100, 10 (pF)
Max. electrode feed	7, 14, 30 ($\mu\text{m}/\text{sec}$)
Layer depth (Depth of cut)	1, 2, 5 (μm)
Workpiece material	Stainless Steel AISI 304
Electrode material	Tungsten
Electrode diameter	50 μm
Slot length	680 μm
Designed slot depth	150 μm

(a) MRR vs. Voltage

(b) MRR vs. Capacitance

(c) MRR vs. Feed

Figure 2.3 Influence of micro EDM process parameters on MRR in slot machining [64]

The results show that the effect of capacitance, rather than voltage, is more pronounced on MRR and an increase in feed gives higher MRR.

With proper understanding and control of the process parameters it is possible to achieve dimensional and geometrical limits as given in Table 2.3 that reflects the state of the art achievements by micro EDM.

Table 2-3 Process characteristics of micro EDM [65]

	Wire EDM	Micro die sinking
Mean contour deviation (μm)	± 1	± 2
Position accuracy (μm)	± 1	± 1
Average surface roughness R_a (μm)	0.1-0.2	0.2-0.3
Average peak-to-valley height R_z (μm)	0.5-2.5	1-5
Smallest structural dimensions (μm)		
Teeth	20-40	20-40
Grooves	50-60	20-40
Maximum aspect ratio		
Teeth	20-30	15-25
Grooves	60-80	10-25
Holes	---	10-50
Smallest electrode dimensions (μm)	25, 30	10

2.2 Technological Advances in EDM

In this section a critical review of the literature relevant to following aspects of micro EDM is presented.

- 1) Micro groove machining
- 2) Flushing techniques
- 3) Numerical study

2.2.1 Micro groove machining

Micro grooves are predominant features in micro system applications such as micro heat exchangers, linear actuators, ratchets, optical switches, fibre alignment devices, and particle separators. The standard setup of micro EDM uses a pin-shaped electrode as a tool in micro groove machining. This highly versatile method has the flexibility to machine holes, grooves as well as complex three dimensional shapes as shown in Figure 2.4.

Figure 2.4 Three dimensional micro structure (1/ 8th of a sphere in a square cavity) machined by micro EDM [66]

However, when the requirement is to machine straight micro grooves exclusively, there is the probability for process improvement. As pin electrodes with diameters

smaller than 100 μm are seldom readily available, to make holes and grooves of width smaller than 100 μm , the diameter of the available electrode is reduced to an appropriate size using the built-in wire electro discharge grinding attachment [67]. While this online electrode grinding improves the accuracy, it does consume considerable machine hours too. A tandem approach developed by Prof. Mazusawa aims to reduce this grinding time by simultaneous grinding and drilling as shown in Figure 2.5. However, this approach requires necessary add-on accessories.

Figure 2.5 Principle of Tandem micro EDM [68]

Technological advancements that can complement the standard technique of using pin electrodes in the micromachining of straight grooves are

1. Wire electro discharge machining
2. Brush electro discharge mechanical machining
3. Micro EDM using rotary disc electrode

These techniques are discussed below.

2.2.1.1 Wire electro discharge machining

The wire electro discharge machining technique is the most prominent technique used for the spark erosion of grooves. Using ultra thin wire (ϕ 30 μm) as a tool electrode, this technique can be used for micro groove machining [69]. The discharge forces [70] will become significant when using such thin wires and the process may be disturbed by wire vibrations and frequent wire breakages [71-73]. Online monitoring and control [74-76], and optimizing the process using finite element modeling [77] are attempted to improve these difficulties.

2.2.1.2 Brush Electro-Discharge Mechanical Machining

Brush Electro-Discharge Mechanical Machining (BEDMM) is schematically shown in Figure 2.6.

Figure 2.6 BEDMM Process [78]

The BEDMM process is based on cutting with electro erosion and friction interaction on the metal. During machining, an electric arc melts particles of the workpiece material, which are subsequently removed by friction between disc and machined surface. The recast layer resulting by this process is about 5 to 20 μm [79]

and as the process involves frictional forces, it may not be suitable for the machining of fragile components.

2.2.1.3 Rotating disc electrode method

The process of electro discharge machining using a rotating disc electrode is schematically shown in Figure 2.7.

Figure 2.7 Groove machining using rotating disc electrode [80]

The electrode is rotated and sunk simultaneously to machine a rectangular slot in a workpiece. The rotation imparts a velocity to the dielectric in the gap, effectively flushing the gap. This facilitates better debris removal. As the tool wear is not localized and is evenly spread over the entire circumference of the disk, better reproduction of corners is viable in this process. Micro grooves of widths as small as $42\text{ }\mu\text{m}$ have been machined by EDM using a rotating disc electrode $25\text{ }\mu\text{m}$ thick [81].

A limitation to all the three processes discussed above is that they are not suitable for machining blind micro grooves as shown in Figure 2.8.

Figure 2.8 Blind micro grooves

The electro discharge machining process using foil electrodes is capable of machining such blind grooves.

2.2.1.4 Foil electrode method

In this process micromachining is done using foil as the tool electrode. Micro grooves having widths less than $50\text{ }\mu\text{m}$ as shown in Figure 2.9 can be machined by this process.

Figure 2.9 Micro grooves machined by EDM using foil electrode

Apart from the straight micro grooves shown above, this technique can be used to machine circular micro grooves as shown in Figure 2.10. A list of commercial sources of foil electrodes is given in Appendix A.

Figure 2.10 Circular groove made using foil electrode

To machine more complex features such as involute and other polynomial shaped grooves, a foil holder with corresponding shapes needs to be used. The process of micro groove machining by micro EDM using a foil electrode is discussed in detail in Chapter 4 of this thesis.

2.2.2 Flushing methods

Flushing is a useful procedure for removing debris from the discharge zone and the material removal rate in roughing is increased by flushing [82]. On the other hand, the most common cause of EDM failures is inadequate flushing [83]. Flushing is necessary to reduce the arcing tendency and to get good sparking. Arcing is an undesirable phenomenon caused by discharge concentration, leading to spark deterioration and an unstable process [84]. Arcing happens as a series of discharges strike the same spot repeatedly. Continuous and violent arcing will destroy both the tool and the work. Since too much debris in a spark gap causes arcing, flushing is done to keep the sparking zone clean. Though flushing is predominantly achieved by mechanical means, an alternate method such as magnetic field can also be effectively used [85]. This section covers the description of existing flushing methods used in traditional die sinking machines and limitations in their applicability to micro EDM.

Existing flushing methods are broadly based on following three concepts:

- Controlling the fluid flow
- Modifying the electrode shape
- Imparting relative movement between workpiece and tool electrode

2.2.2.1 Type of fluid flow

Based on the fluid flow, existing flushing methods can be broadly classified into normal flow, reverse flow, jet flushing and immersion flushing, as discussed below.

2.2.2.1.1 Normal Flow

This is the most common method and is achieved by pressure or injection flushing. An electrode with a central hole is used as a tool electrode. Dielectric fluid under

pressure is injected through this hole as shown in Figure 2.11. The fluid flowing out from the sparking zone will flush out the debris. Pressure as high as 5 MPa has been used to achieve higher MRR in fast EDM drilling [86].

Figure 2.11 Normal Flow of dielectric fluid [87]

This type of dielectric flow provides the possibility for secondary sparking which results in tapering of the workpiece as shown schematically in Figure 2.12.

Figure 2.12 Secondary sparking produces taper in workpiece [87]

Another problem is that the holes drilled in the tool electrode for fluid flow will leave *spikes* or *studs* in the workpiece. This can be avoided either by providing tapering holes in the tool electrodes as shown in Figure 2.13 or by rotating the electrode as shown in Figure 2.14.

Figure 2.13 Tapering the flush holes prevents long spikes [87]

Figure 2.14 Rotating an electrode by 180 degrees to remove studs [87]

In a recent development, Kunieda et al. have injected high pressure (1MPa) oxygen gas, instead of the dielectric liquid, to get a higher MRR as a result of thermally activated oxidation of the workpiece material [88, 89]. Use of gas reduces the reaction forces and vibration, thus high precision finishing is achieved [90].

2.2.2.1.2 Reverse Flow

To avoid taper caused by normal flow, reverse flow as shown in Figure 2.15 can be employed by suction flushing. This technique too leaves spikes, which can be removed as seen in the previous section. This technique can be used for finishing. Optimum fluid velocity (correspond to MRR) need to be used to minimise the conicity of the drilled hole [91].

Figure 2.15 Reverse flow of dielectric fluid by suction flushing [87]

2.2.2.1.3 Jet Flushing

Jet flushing is done by tubes or flushing nozzles which direct the dielectric liquid into the gap as shown in Figure 2.16.

Figure 2.16 Jet flushing [87]

Masuzawa et al. have used moving nozzles to sweep along the sparking gap [92]. This dynamic flushing results in an even distribution of debris concentration, thus avoiding the undesirable accumulation of debris in the sparking zone.

2.2.2.1.4 Immersion Flushing

When machining fragile components and also during shallow machining this type of flushing is used, which is an immersion of the workpiece into the dielectric liquid tank.

2.2.2.2 Electrode shape modifications

By modifying the electrode shape, like using a hollow electrode or electrode with multiple cavities or notch as shown in Figure 2.17(a) and (b), better flushing can be achieved [93].

Figure 2.17 Electrode shape modifications

An electrode made of mesh sheet as shown in Figure 2.17 (c) allows quick escape of the gases and debris formed during the machining through the woven wires and facilitates high speed EDM under lower electrode wear conditions and has been found to be useful in machining of insulator ceramics [96].

2.2.2.3 Imparting relative movement between workpiece and tool electrode

The relative movement between the electrode and workpiece can be provided by

- Ultrasonic vibration of tool or workpiece
- Withdrawal of tool electrode
- Rotation of tool electrode or workpiece
- Orbiting motion of tool electrode

These four methods are discussed in the following sub sections.

2.2.2.3.1 Ultrasonic vibration of tool or workpiece

Ultrasonic vibration is a well-known method to improve the performance of EDM [97, 98]. It is found to be a useful aid in exotic material machining [99-102]. The high frequency pumping action of the vibrating surface accelerates the slurry circulation and reduces the machining time [103]. The vibrations can be imparted either to the workpiece [104, 105] or tool electrode [106, 107]. These vibrations introduce acoustic streaming in the dielectric tank and particles move along this stream [108]. Apart from acoustic streaming, the debris particles are also subjected to ultrasonic irradiation, Bernoulli's attraction and Stoke's force [109]. As a result of this induced fluid flow, better debris removal is achieved, which in turn results in higher aspect ratio machining [110] and better surface finish [111, 112].

2.2.2.3.2 Withdrawal of tool electrode

In this method which is also known as vertical flushing, the tool electrode moves up and down periodically in the cavity as shown in Figure 2.18. This vertical movement of the electrode causes pumping action and as a result fresh dielectric liquid is drawn into the cavity. This natural flushing produces an even and uniform surface.

Figure 2.18 Vertical flushing [87]

Die-sinking machines equipped with linear motors can provide high speed (1400 ipm) electrode jumping motion [113]. However, an electrode jump and debris exclusion model and experimental verification by Certin et al. reveals that the electrode jump height, rather than the jump speed, plays more important role in deep machining [114].

2.2.2.3.3 Rotation of tool electrode or workpiece

When the tool electrode [115, 116] or workpiece [117, 118] is rotated, better flushing is achieved by Taylor-Couette flow and due to the accompanying centrifugal force higher MRR is achieved. Figure 2.19 shows the rotary flushing.

Figure 2.19 Rotary flushing [87]

This is the most prominent method used in micro EDM [119]. By combining ball burnishing action along with the rotary motion of the electrode, Yan et al. have achieved 50-92% surface finish improvement in the machining of $\text{Al}_2\text{O}_3/6061\text{Al}$ composite [120].

2.2.2.3.4 Orbiting motion of tool electrode

Orbiting the electrode as shown in Figure 2.20 is yet another method that helps to improve accuracy and surface quality.

Figure 2.20 Orbiting flushing [87]

Planetary motion of the tool electrode allows the dielectric liquid to flow in from one side and leave at the other side of the workpiece [121]. This technique is used in CNC machines for finish machining [122].

2.2.2.4 Limitations of existing flushing techniques

Most of the flushing techniques seen in section 2.2.2 have been successfully employed in macro machining. However, in the field of micromachining some have certain limitations which are listed in Table 2.4.

The flushing techniques applicable in micro EDM machining using a pin electrode are given below:

1. Rotating the electrode, with spindle speed of 2000 – 3000 RPM.
2. Ultrasonic vibration of tool / workpiece.
3. Vertical movement of tool electrode.
4. Axial flushing through a pilot hole. Pre-drilling of tool electrode can be done by laser ablation [123].

Table 2-4 Limitations of existing flushing techniques

Flushing technique	Remarks
Controlling the fluid flow	Too small electrode dimensions and fragility are the limitations to drill holes and apply pressure in the electrodes.
Electrode shape modifications	Hollow electrodes may leave spikes. Unsymmetrical shape modifications (notch) may produce undesirable vibrations during rotation
Imparting relative movement between workpiece and tool electrode	Ultrasonic vibrations may result in enlarged dimensions Frequent withdrawal of tool electrode involves additional tool movement and time With electrode rotation only axis-symmetric machining is possible Orbiting tool movement is applicable only for larger holes.

To support the existing techniques and to overcome the limitations mentioned in Table 2.4, some novel techniques have been applied to micro EDM. These are explained in Chapter 5 of this thesis.

2.2.3 Numerical study

Though EDM has been successfully practiced for more than half a century, the mechanism of the process is not yet fully understood [24]. Compared to the vast literature available on experimental studies, literature on analytical and numerical approaches to understand the EDM process is relatively scarce. The stochastic nature of the process and the complex plasma formation during discharge make it very difficult to fully understand the process. Almost all modelling efforts are based on the Fourier's partial differential equation of heat conduction in solids [124] and a single spark discharge is assumed [125]. Singh and Ghosh have used a plasma fluid equation (similar to the Navier-Stokes equation of fluids) to model the electrostatic force and stress distribution in the metal during discharge [126].

Heat transfer theory was used by Ikai and Hashiguchi to simulate the crater formation and to determine the relationship between the crater radius and the heat source radius [127, 128]. DiBitonto et al. have used a simple point heat source in which heat is partially dissipated [27, 129, 130]. Others assume a cylindrical heat source of constant radius [131] or heat source with the radius expansion as a function of time, discharge current and dielectric pressure [91, 132-134]. As an additional heat input, Joule heating was also taken into account [135]. Joule heating occurs when an electrical current (I) is passed through a material and the material's resistivity (R) to the current causes heat generation. According to Joule's law, the heat generated for a time (t) is equal to $I^2 R t$.

Almost all of these works assume isotropic material properties. Schonbeck considered non-isotropic material properties to study electrically conductive ceramics [133]. Based on the metallurgical examinations of spark eroded surfaces, surface integrity models have been proposed [136-139]. Of late the FEM technique

is increasingly being used to model the stresses induced in spark eroded surface [140-143].

Modeling the EDM process for multiple successive discharges is yet to yield satisfactory results. As the traditional approaches are inadequate to model, simulate and control the real life random sparking behaviour of the EDM process, other means like modern control concepts [144] such as adaptive control [145-149], statistical control [150, 151], expert systems [152, 153], fuzzy control [154-158], neural networks [59, 159-161] and their combinations [162-164] have been used to study the process.

Based on the above mentioned works, it can be seen that certain aspects of the EDM process such as modeling of the heat source and determination of plasma size, crater size determination and microstructure analysis, effect of process variables on the performance of EDM have been reported in the past for conventional EDM at the macro level. Literature on numerical studies of micro machining by EDM is conspicuous by its absence. Moreover, the focus of earlier macro EDM studies was mostly on hardened ferrous materials as the primary application of conventional EDM is in the Tool & Die industry. However, with the rapid proliferation of the Micro System Technology (MST) market, several new applications have emerged for micro EDM [165]. Non-ferrous materials such as titanium alloys which have a wide range of applications covering structural, aerospace, and biomedical fields [166] are required to be micromachined using micro EDM. Hence, it is required to study the effect of micro EDM on these materials.

As micro EDM is a thermal process, it leaves residual stress on the workpiece. Residual stress is defined as a stress state which exists in the bulk of a material without application of an external load or other source of stress such as a thermal

gradient [167]. It is essential to estimate the residual stress due to spark erosion as it reduces the fatigue strength of electro-discharge machined components [168-170].

Estimation of residual stress can be done numerically as well as experimentally [63, 139-141, 143, 171]. Comparison of different residual stress determination methods, their advantages and limitations are given in Table 2.5. From the table it can be seen that only a few techniques are available when the sample size reaches the micro domain. Nanoindentation is one such technique that can be used to determine the residual stress in micro region [172]. Nanoindentation is a quantitative means of determining mechanical properties via analysis of load-displacement data obtained from indentation contacts [173]. The advantage of using nanoindentation is that the specimen size can be very small and the indentation does not alter the stress field as extremely small loads (on the order of μN) are used in this method. The numerical study of the micro EDM process and the application of a nanoindentation technique for investigation of residual stress are discussed in detail in Chapter 6.

Table 2-5 Comparison of residual stress measurement techniques [174]

Key Techniques	Material Type	Resolution	Penetration	Sampling Area/Volume	Advantages	Limitations
Hole Drilling	Metals Plastics Ceramics	50-100 μm depth increment	= hole diameter	1-2 mm diameter 1-2 mm deep	Quick, simple, widely available, portable, wide range of materials, deep hole drilling for thick section components	Interpretation of data, destructive, limited strain sensitivity and resolution
X-ray Diffraction	Metals Ceramics	20 μm depth 1 mm laterally	5 μm – Ti, 50 μm – Al, 1 mm – layer removal	0.1-1 mm^2 0.05-0.1 mm	Versatile, widely available, wide range of materials, portable systems, macro and micro RS	Basic measurements, lab-based systems, small components
Synchrotron	Metals Ceramics	20 μm lateral to incident beam. 1 mm parallel	>500 μm , 100 mm - Al	0.1 mm^3	Improved penetration & resolution of X-rays, depth profiling, fast, macro and micro RS	Specialist facility only, lab-based. measures strain only. Rarely possible to obtain stresses.
Neutron Diffraction	Metals Ceramics	500 μm	100 mm – Al, 25 mm – Fe, 4 mm – Ti	> 1 mm^3	Excellent penetration & resolution, 3D maps, macro and micro RS	Specialist facility only, lab-based
Curvature and Layer removal	All	Depends on material & measurement method	Not applicable		Relatively simple, wide range of materials, can be combined with other techniques to give stress profile	Limited to simple shapes, destructive, lab-based
Magnetic	Ferromagnetic Materials	1 mm	20 – 300 μm (Barkhausen)	> 2 mm^2	Very fast, wide variety of magnetic techniques, portable	Can apply to ferromagnetic materials only, need to separate the microstructure signal from that due to stress
Ultrasonic	Metals Ceramics	5 mm	> 100 mm along specimen	1-400 mm^2	Generally available, very fast, low cost, portable	Limited resolution, bulk measurements over whole volume
Raman/Fluorescence	Ceramics Polymers	0.5 μm	Surface		High resolution, portable systems available	Surface measurements, interpretation, calibration, limited range of materials

2.3 Outcome of the literature review

The major outcome of the literature review that has explicit bearing on this thesis is given below:

1. EDM research is vibrant and micro EDM is evolving as viable micromachining technology. Technological advances are needed in micro groove machining with the invention of novel EDM techniques. Contributions made in this effect are discussed in Chapter 4.
2. Flushing of debris is the key factor, which, if not done properly, can undermine the progress made in all other areas. Conventional flushing techniques may not be suitable for micromachining due to size limitations and fragility. Hence, flushing techniques that are applicable to micro EDM process need to be developed. Contributions made in this effect are discussed in Chapter 5.
3. Numerical studies and EDM process simulation have been done at the macro level. Conventional experimental verification techniques (such as hole drilling, X-ray diffraction) are not suitable for experimental verification of numerical studies at micro level. Literature review reveals that nanoindentation technique has the potential for such studies. This aspect is discussed in Chapter 6.

In the following chapter, the experimental methodology and the characterization techniques used in this research are explained.

Chapter 3

Experimental methodology and characterization techniques for micro spark eroded surfaces

The experimental methodology used for the micro sparking and the equipment used for the characterization of the micro spark eroded surfaces are described in this chapter. This chapter has two sections. Description of the equipment used for micro EDM and the experimental procedures are covered in the first section. The various measurement details and equipment used for the characterization of spark eroded surface are explained in the subsequent section.

3.1 Micro EDM experimental details

The experimental work was conducted using a commercially available micro EDM system, MG-ED72W, as a platform to machine micro grooves. The experimental setup is shown in Figure 3.1. The micro EDM process uses the RC electro-discharge circuit for micromachining. Four values of capacitor selection (3300, 220, 100 and 10 pF) and a voltage setting, ranging from 0 to 110 V, can be chosen. The machine can be programmed for the positioning increment of 0.1 μm in the X-, Y- and Z-axes. The positioning range for the respective axes are 200, 50 and 50 mm. There is a built-in WEDG system which can be used for grinding the tool electrode to the desired size.

Figure 3.1 Micro EDM experimental setup

A standard tool-holding mechanism was used for experiments done using pin-shaped electrodes. For experiments with rectangular foil electrodes, a modified tool holder was used. In this holder, the ceramic portion of the standard holder was removed and a smooth flat surface (notch) was made at the end of the holder by surface grinding. The foil and a backup plate (to support the foil) were fastened to this flat surface. The standard as well as the modified tool electrode holder is shown in Figure 3.2.

Figure 3.2 The standard and modified tool electrode holders

3.2 Characterization techniques

Characterization study, in simple terms, is the numerical description of the relevant features, performed by measurement and inspection. While the results are quantitative in most of the cases, it can also be expressed in a qualitative manner, as in the case of scanning electron microscope (SEM) results [175]. Characterization of the surface of a machined component includes measurement of the topography, surface roughness, feature dimensions, material diffusion, microhardness and microcracks [170]. This is a challenging task when the dimensions are on the order of few hundreds of micro meters and less. Handling such tiny components requires skills and more often, the inspection requirements demand high precision metrological equipments. In this section the characterization studies done on micro spark eroded surfaces using the state of the art equipment are described.

3.2.1 Surface Roughness measurement

Roughness of smooth surfaces can be accurately measured using the principles of laser interferometry as shown in Figure 3.3.

Figure 3.3 Roughness of polished surface measured by laser interferometer.

But the typical spark eroded surface is relatively coarser and hence, focusing will be tedious in a laser interferometer. A stylus instrument as shown in Figure 3.4 will be useful in such cases, provided the surface to be measured is external or at a shallow depth.

Figure 3.4 Talyscan 150 surface scanning instrument

Surface roughness measurement done using Talyscan 150 is shown in Figure 3.5.

Figure 3.5 Surface roughness ($R_a = 0.485 \mu\text{m}$) measured by stylus instrument

For measuring the internal surfaces and deep surfaces, a mould impression of the surface is usually obtained and measured. Instead of this indirect measurement, which may not be accurate (as the mould may shrink or break during the measurement) a direct non-contact optical roughness measurement as shown in Figure 3.6 is carried out in the present work by using a white light confocal microscope.

Figure 3.6 Surface roughness measured by confocal microscope

For the surface roughness measurement with nanometer level precision the atomic force microscope can be used. Figure 3.7 shows the results obtained by AFM.

Figure 3.7 Surface roughness measurement done by AFM

Analysis of the roughness values obtained by AFM is shown in Figure 3.8.

Figure 3.8 Box and whisker plot of the roughness parameters provide information about the minimum, lower quartile, median, upper quartile, and the maximum values of the data

3.2.2 Measurement of the surface topography

Qualitative inspection of the surface can be done by surface imaging using a scanning electron microscope (SEM) as shown in Figure 3.9.

Figure 3.9 Surface images taken using scanning electron microscope

While the SEM is very useful to inspect large surfaces (a few mm) and detect surface defects such as micro cracks, it cannot provide quantitative information. In such cases the atomic force microscope shown in Figure 3.10 is highly useful.

Figure 3.10 Atomic force microscope

The topography of a spark eroded surface is shown in Figure 3.11. The surface is isotropic in nature and is formed by the overlapping of individual craters. The surface does not show any specific texture or pattern.

Figure 3.11 Surface topography measured by AFM

3.2.3 High aspect ratio measurement

Measurement of high aspect ratio features involves considerable labor and skill. Destructive measurement using precision laser beam machining [176] and precision grinding is done to reveal the cross section. Sectioning is to be done at the hole centre, to ensure accurate measurement of aspect ratio achieved. It is difficult, if not an impossible task, by this approach to section at the hole centre.

A cross section of a spark eroded hole machined in the present work was obtained by sectioning and is shown in Figure 3.12.

Figure 3.12 Destructive measurement

Almond et al. have found a better method in which the two edges are polished and butt together in contact. EDM of several holes are done along the joining line to increase the probability of obtaining at least one hole at the approximate centre [177]. This approach again is time consuming as many holes need to be drilled. Moreover this method again is a destructive inspection, in the sense that the component inspected cannot be put into use. In the present work, a confocal microscope shown in Figure 3.13 was used for the non-destructive measurement of high aspect ratio features.

Figure 3.13 Sensofar confocal optical profiler

The measurement is done by repeatedly focusing the component along its depth using white light. The component profile is obtained by compiling all the focal points as shown in Figure 3.14.

Figure 3.14 Principle of confocal measurement [178]

The measurement of a high aspect ratio hole obtained by confocal microscope is shown in Figure 3.15.

Figure 3.15 Non-destructive measurement of micro feature (Aspect ratio 13.5)

The advantages of the technique are

1. An image from a prescribed section of an object can be obtained, without the presence of out-of-focus information from surrounding planes [179].
2. Measurement can be done in a few minutes.
3. As the process is nondestructive, several readings can be obtained for the same hole by the precise control of table movement. There is no need of machining several holes to obtain the cross section profile at the centre line.

The limitations are

1. A drawback of confocal reflection microscopy is the lack of specific probes that differentially reflect light for multiple label experiments. Confocal fluorescence imaging is preferable for such cases.
2. Any debris lying deep inside can affect the readings. Cleaning the component in an ultrasonic vibration bath can minimize this possibility.
3. Some operation skill is required as in the case of any sophisticated equipment.

3.2.4 Dimensional and geometrical measurement

Dimensional measurement such as the width of a micro groove or diameter of the hole at surface level can be easily done by using optical microscopes. Sophisticated microscopes have built-in software to do geometrical measurements such as straightness and circularity. Figure 3.16 shows a microgroove and its straightness measurement done by an OMIS optical microscope. The straightness measured is $16.8\text{ }\mu\text{m}$ for a groove length of 10 mm.

Figure 3.16 Straightness measurement done using an OMIS optical microscope
(a) Microgroove, (b) Measurement display

3.2.5 Nanoindentation

Indentation is the traditional method used for over 100 years to determine hardness of materials [180]. Hardness is determined from the ratio of applied load to the projected area of contact, for the given indenter geometry. Measuring the projected area becomes tedious when the dimensions reach the nanometer range. A relatively new process known as *depth-sensing nanoindentation* is useful in such cases [181]. In this process, a controlled variable force is applied to the sample through an indenter. This is followed by an unloading sequence as shown in Figure 3.17(a).

Variations to this process such as partial unloading during loading sequence, optional hold at the maximum load as shown in Figure 3.17 (b) are also used in the nanoindentation test cycle [182].

**Figure 3.17 Nanoindentation test cycle (a) typical loading and unloading cycle [183]
(b) with additional components [182]**

The loading portion of the curve results from both plastic and elastic deformation response of the indenter contact, while the unloading portion of the curve is related to the elastic recovery of the contact. The important quantities given by the load-displacement data are the maximum load, the maximum displacement, the elastic unloading stiffness or contact stiffness (slope of the upper portion of the unloading curve) and the residual depth [184]. These quantities are applied in well-established mechanical models to determine (for a given indenter geometry) the hardness and elastic modulus [185, 186]. The results were found to be within 7-14% standard deviation in an international round-robin experiment [187]. The load and displacement resolutions are reported to be 50 nN and 0.04 nm respectively [188]. The load-displacement data of a tool steel (XW41) surface measured before and after spark erosion is shown in Figure 3.18.

Figure 3.18 Load-displacement data of a spark eroded surface obtained by nanoindentation

As seen from the Figure 3.18, the surface after EDM shows stiffer plastic response, which manifests itself in the greater loading parabolic curvature. This response results in a smaller indentation area for the same maximum load, suggesting that the material is more resistant to plastic deformation.

It may be noted that the unloading curves in Figure 3.18 do not return to zero load as shown in Figure 3.17. This is because the last data point in unloading curve is taken before the indenter leaves the surface at some finite load. It is not possible for the instrument to apply precisely zero load since then the indenter will be off the surface. The hardness and elastic modulus of the material before and after EDM were found to be 6.88, 198.74 GPa and 8.88, 219.04 GPa respectively in this case. The plateau seen at the peak of the load-displacement curve is caused by creep in the specimen as well as by the thermal drift of the apparatus during the test.

3.2.6 Spark On-time measurement

Measurement of spark *On-time* is necessary, to calculate the heat input, for the thermal simulation of the machining process. In electro discharge machines using transistor based circuits, the spark *On-time* can be preset. Since the micro EDM machine used in this research is built with RLC circuit rather than the transistor based switching circuit, it is not possible to preset the spark *On-time*. In order to know the spark *On-time*, measurement of current during the sparking was done using a current probe and the waveform is captured using an oscilloscope. The setup is shown in Figure 3.19.

Figure 3.19 Waveform measurement using a current probe and an oscilloscope

The spark *On-time* is obtained from the current waveform as shown in Figure 3.20.

Figure 3.20 Current waveform showing a spark *On-time* of 100 ns

3.3 Summary

The experimental methodology is explained in this chapter. The equipment used for the characterization and the representative measurement results are also shown. The novel micro groove machining technique by spark erosion, using a microfoil as tool electrode is discussed in the following chapter.

Chapter 4

Micro groove machining using microfoil as a tool electrode

This chapter explores the usage of a micro foil as a tool electrode in micro groove machining using micro EDM. The existing technique of micro groove machining and its limitations are explained below, followed by an introduction of a novel technique called FAST EDM (**F**oil **a**s **t**ool electrode) wherein the concepts involved are explained. The details of the experiments done and results obtained are discussed subsequently. This chapter concludes with a list of advantages and limitations in using foil as a tool electrode.

4.1 Micro groove machining by micro EDM using existing method

In the existing method, a pin-shaped electrode is used as a tool. The workpiece is clamped to the worktable immersed in the dielectric tank. Necessary movements of the workpiece in the longitudinal and lateral directions (X -axis and Y -axis) are provided using computer numerical control to obtain the desired geometry and the vertical movement (Z -axis) is given to the tool electrode to obtain the required depth. The minimum groove width obtainable is given by

$$W_{\min} = d_{te} + 2t_{sg} \quad (4.1)$$

where,

$W_{\min}$ = minimum obtainable groove width

d_{te} = diameter of tool electrode

t_{sg} = spark gap

4.1.1 Limitations of existing method and need for an alternate approach

Pin electrodes with diameter smaller than 100 μm are seldom readily available. To make holes and grooves of width smaller than 100 μm , the diameter of the available electrode is reduced to an appropriate size using the built-in wire electro discharge grinding attachment [67]. While this inevitable online electrode grinding improves the accuracy, it consumes considerable machine hours. As discussed in section 2.2.1 of the literature review, the tandem approach by Prof. Mazusawa [68] aims to reduce this grinding time by simultaneous grinding and drilling but this approach requires necessary add-on accessories.

High processing time due to low material removal rate is one of the constraints in micro EDM. Since low processing energy is the hallmark of micro EDM, increasing the material removal rate by augmenting the process energy (by increasing voltage, current, capacitance) is a self-defeating approach. One alternative is providing more “*sparking opportunities*” by increasing the contact area. FAST EDM addresses both these issues of electrode grinding and increasing the contact area.

4.2 Concept of FAST EDM

FAST EDM is a novel micro EDM process in which the conventional pin electrode is replaced by a foil as the tool electrode. Commercially available rectangular foils are used as the tool electrode in FAST EDM. The electrode movements in the micro groove machining process, using this approach as well as in conventional micro EDM with a rotating pin electrode are shown in Figure 4.1.

Figure 4.1 Electrode movement in conventional micro EDM and fast micro EDM [189]

In conventional micro EDM, a micro groove is made by the combined effects of three movements. The pin electrode rotates and also moves in the Z-axis. The second and third movements are provided by the work table in the X and Y-axes. Compared to this, the FAST EDM typically requires only one plunging movement in the Z-axis.

4.3 Experimental work

Using the foil-shaped electrode, experiments were carried out without tool rotation. Foils were handled with care to avoid bending or breakage. The tool electrode setting was performed in two steps. A standard fixture supplied by the machine builder as shown in Figure 4.2 was used to house the tool holder and an optical microscope attached with the fixture was used for the initial positioning and adjustment of the foil electrode so that the edge of the foil is aligned perpendicular to the axis of the tool holder. The tool was then mounted on the machine and facing off the foil using sacrificial machining of a block was done to ensure the parallelism between the tool bottom edge and the top surface of the workpiece.

Figure 4.2 Electrode aligning fixture

Proper initial alignment of the foil in the tool holder is important to reduce the amount of sacrificial machining*. The alignment procedure is schematically shown in Figure 4.3.

Figure 4.3 Foil alignment procedure

The shaded portion shown in Figure 4.3 is the foil material removed by sacrificial machining. Proper alignment using the optical microscope will minimise this shaded portion and hence, the sacrificial machining time. For the alignment along the groove direction, the foil is observed by an optical microscope. Initially the

* The multi-media file “*sacrificial machining.wmv*” available in the accompanying CD ROM shows facing off the foil. FAST EDM done using an even foil is shown in “*good machining.wmv*”

microscope is focused to any spot in the foil. Then the microscope is moved along the desired groove direction. If the foil is not aligned along the groove direction, then it will go out of focus as the microscope moves. The foil needs to be adjusted till it stays in focus for the entire movement of the microscope. The machining parameters used are shown in Table 4.1. The CNC program used is given in Appendix B.

Table 4-1 Machining parameters used in FAST EDM

Work piece	Brass
Tool Electrode	Stainless steel Foil 10 μm thick
Voltage	110 V
Polarity	Work piece is anode & Tool Electrode is cathode
Capacitance	3300 pF
Dielectric	HL 25-S
Feed rate	30 $\mu\text{m s}^{-1}$

The rather unusual choice of the tool electrode material is due to the fact that it is widely used as a shim in the tool & die industry and hence, it is readily available in a wide range of thicknesses. The properties of the stainless steel foil are shown in Table 4.2.

Table 4-2 Specification and composition of stainless steel foil

Specification	Composition
X 5 Cr Ni 18 9	C = max. 0.07%
US-Norm AISI 304	Si = max. 1.00%
AFNOR Z 6 CN 18-09	Mn = max. 2.00%
	P = max. 0.045%
	S = max. 0.03%
	Cr = 17–20.0%
	Ni = 8.5–10.0%

4.4 Results and discussion

The microgrooves machined using the stainless steel foil are shown in Figure 4.4. The photograph was taken using the OMIS optical microscope. It shows a portion of the 30 micro grooves with pitch 50 μm , width 50 μm and length 7 mm made in brass.

Figure 4.4 Microgrooves made using stainless steel foil

The three-dimensional view of the microgrooves obtained using the scanning electron microscope with magnification 270 X is shown in Figure 4.5.

Figure 4.5 Three-dimensional view of the micro grooves obtained using SEM

From Figure 4.5 it is clear that the micro foils can be successfully used as tool electrodes in microgroove machining by micro EDM. All the grooves were made without any human interruptions such as electrode re-grinding. The feed of the electrode with respect to time is shown in Figure 4.6.

Figure 4.6 Feed of tool electrode in FAST EDM

Figure 4.6 shows the lack of consistency in the machining pattern for four experiments conducted under the same condition. The fluctuating feed rate is not an indication of good machining. A confocal microscope (model PLμ) from Sensofar working on the principles of white light interferometry (explained in section 3.2.3) is used for the measurements. The measurement of the groove is shown in Figure 4.7. The groove depth obtained is about 15 μm. This is only one-fourth of the tool feed of 60 μm as indicated by Figure 4.6. This comparison reveals that there is excessive wear of the tool electrode. This indicates that a lot of debris is produced due to tool electrode wear when stainless steel is used as the tool electrode.

Figure 4.7 Measurement of the microgroove. Confocal imaging system was used to take measurements. The surface roughness at the bottom of the groove is $R_a = 0.47 \mu\text{m}$

The width of the groove obtained is $64 \mu\text{m}$ where as the thickness of the foil used is only $10 \mu\text{m}$. As per the equation 4.1 this works out to a sparking gap of $27 \mu\text{m}$, which is an unreasonably high value for micro EDM. The reason for this phenomenon is the high amount of uncontrolled secondary sparking occurring due to the presence of excessive debris produced by rapid wear of the stainless steel tool electrode. This is undesirable and results in the wastage of valuable machining hours and may even cause arcing and a heavy distortion of the geometry made as shown in Figure 4.8.

Figure 4.8 Arcing is undesirable and may cause severe distortion of the feature geometry

A simple solution to reduce the time loss due to arcing is to provide relative movement to the workpiece. Instead of using the hole-drilling command in the CNC program (listed in Appendix B), slot-machining command (listed in Appendix C) is used to provide table movement l_{m1} and l_{m2} as shown in Figure 4.9.

Figure 4.9 Direction of movements of workpiece and foil electrode

It is observed that the arcing tendency is considerably reduced by this approach. As the length of the groove made is longer than the foil length, the foil size must be smaller than the desired groove length and the total amount of workpiece movement must be given as per the Equation 4.2

$$l_m = l_{m1} + l_{m2} = l_g - (l_f + 2t_{sg}) \quad (4.2)$$

where,

l_m = total workpiece movement

l_g = length of the groove

l_f = length of the foil electrode

t_{sg} = spark gap

The feed obtained with table movement is shown in Figure 4.10.

Figure 4.10 Results of FAST EDM with table movement

Figure 4.10 indicates that the feed obtained is more uniform with table movement. The possible reason for this is that increased spark mobility is achieved with table movement. When arcing is likely to occur, the work piece “moves away” from the potential arcing site. This reduces the possibility of arcing in the foil-workpiece interface. Even if the arcing does occur, it is not allowed to last due to the relative movement of the workpiece and foil. The measurements of the grooves made with table movement are shown in Figure 4.11.

Figure 4.11 Measurement of the microgroove made with table movement. Better groove dimensions and surface roughness are obtained due to reduced arcing tendency

From the four set of experiments conducted, it is noticed that there is about 10 to 12% reduction in groove width obtained by sparking with table movement. There is also a marginal improvement in the groove depth and surface roughness.

4.5 Summary

Microfoil was used as the tool electrode in micro electro discharge machining to machine micro grooves in electrically conductive materials. Due to the presence of debris, excessive tool wear and arcing were noticed during these experiments. Introducing relative movement between the tool electrode and the table provides better results. Further process improvements, namely novel flushing techniques, were introduced for effective debris removal as explained in the following chapter.

Chapter 5

Novel flushing methods

Conventional flushing techniques have some limitations as seen in section 2.2.2.4 of the literature review. Flushing techniques that are applicable to the novel micro EDM process introduced in the previous chapter, are required to improve the machining process. In this chapter two novel flushing techniques are described and experimental validation of these techniques is presented. This is followed by a discussion on the effect of these flushing techniques vis-à-vis tool material on MRR and surface finish of the work material.

5.1 Gravity Assisted Micro EDM (GAME)

5.1.1 Concept of GAME

GAME is conceived to improve the flushing conditions of FAST EDM. The schematic illustration of the process is given in Figure 5.1. Since centrifugal forces are absent in FAST EDM, gravitational force is used for the flushing of the debris.

Figure 5.1 Schematic illustration of Gavity Assisted Micro EDM (GAME) [190]

As shown in Figure 5.1, in GAME, the effect of the gravitational force is exploited for debris removal. Here the workpiece is positioned at the top and the tool electrode, namely the foil, is kept at the bottom. The workpiece is firmly held with the spindle and it can move up and down. The tool electrode is clamped with the worktable and can move in the longitudinal and lateral directions. Since erosion is taking place at the bottom of the workpiece, the debris produced fall into the dielectric tank due to gravitational pull and are removed. Thus the sparking zone of the work surface stays clean during the entire process. This minimizes the uncontrolled secondary sparking and improves the process efficiency.

5.1.2 Experimental results

The process parameters used in this study are listed in Table 5.1. The CNC program used is given in Appendix D.

Table 5-1 Process parameters used in GAME

Parameter / Variable	Value
Work piece	Tool steel XW 42
Tool Electrode	POCO Ultrafine Graphite Foil (EDM 3) 100 μm thick
Voltage	110 V
Dielectric	HL 25-S
Capacitance	3300 pF
Feed rate	30 $\mu\text{m s}^{-1}$

The micro groove machined by the gravity assisted micro EDM is shown in Figure 5.2.

Figure 5.2 High aspect ratio (7.95) micro groove produced by gravity assisted micro EDM

It is noticed that an aspect ratio of about 7.95 is achieved for a micro groove of 200 μm width and 20 mm length in Gravity Assisted Micro EDM as compared to an aspect ratio of 2.3 obtained in FAST EDM under similar experimental conditions. The micro groove machined by FAST EDM is shown in Figure 5.3.

Figure 5.3 Microgroove made with Fast EDM. The aspect ratio is about 2.3

The higher aspect ratio achieved in GAME is mainly due to the minimization of arcing, as the debris is effectively removed due to gravitational pull. Distinction between the sparking and arcing can be done by analysing the voltage and current waveform during machining [26]. This approach is good for the adaptive control of the machining process [191, 192]. However, it requires dedicated instrumentation. A simple and practical approach to determine whether the machining is affected by arcing is to observe the electrode feed achieved over a period of time. A comparison of the feed achieved by both the processes under similar machining conditions is shown in Figure 5.4.

Figure 5.4 Comparison of feed in FAST and GAME

The feed achieved (especially after 60 minutes) by GAME is higher than that achieved by FAST EDM. Moreover the feed curve of GAME is almost linear. This indicates that the machining is uniform and not hindered by arcing in GAME.

The advantages of GAME can be further appreciated by comparing the grooves made by the two techniques as discussed in the following section.

5.1.3 Comparison of FAST EDM and GAME

In this section quality and productivity related comparisons of the two processes has been made. An index of the quality of the groove namely the ratio of the maximum groove width to the electrode width for a sample size of 5 is compared in Figure 5.5.

Figure 5.5 Comparison of the ratio of groove width to electrode width

It can be seen from Figure 5.5 that the ratio of the maximum groove width to the electrode width has been considerably reduced (about 40%) in the Gravity Assisted Micro EDM process. In this technique, the debris freely falls in the tank instead of accumulating in the sparking zone. This constantly exposes fresh material at the bottom of the groove for sparking and minimises the sparking of the sidewalls. Hence, a deeper and narrower groove is achieved.

Typical microstructures of the EDM surfaces made in FAST EDM and Gravity assisted EDM are shown in Figure 5.6. An SEM image of the bottom surface machined by FAST EDM is shown in Figure 5.6 (a). It appears to have a concave shape with raised edges. The SEM image of the surface machined by gravity assisted micro EDM is shown in Figure 5.6 (b). It looks much more even and flat.

(a)

(b)

Figure 5.6 SEM images of microstructure of bottom surface made by (a) FAST EDM and (b) GAME

Hence, it can be predicted that this surface is likely to be smoother in comparison to the surface made by FAST EDM. This observation was verified by measuring the roughness of both the surfaces by confocal microscope. Figure 5.7 shows the average roughness values obtained for both the processes.

Figure 5.7 Average roughness value obtained for FAST EDM and GAME

The comparison of the machining time versus depth of the groove made in both the processes is given in Figure 5.8.

Figure 5.8 Comparison of machining time versus depth of the groove made by FAST EDM and GAME

From Figure 5.8 it can be seen that the material removal is done in an effective manner in gravity assisted micro EDM. An interpolation of Figure 5.8 reveals that the machining time saved by GAME in machining a 200 μm deep micro groove is 14 minutes. When the depth of the micro groove doubles, the corresponding savings in machining time is 55 minutes (about a four fold increase in savings of machining time). This reveals that GAME will be vital especially for deeper grooves as it brings down the machining time considerably.

Electrode wear rate (EWR) which is the ratio of wear of the tool electrode to the wear of the machined groove depth, is another indicator of the effectiveness of the machining process. A comparison of the average EWR of both the processes is given in Figure 5.9.

Figure 5.9 A comparison of EWR of FAST EDM and GAME

From Figure 5.9, it can be seen that on an average, the EWR in GAME is about 27% less than that of FAST EDM. Since less EWR facilitates more hours of uninterrupted machining, GAME is preferable for machining high aspect ratio grooves.

A comparison of the straightness of the micro grooves machined by both processes, shown in Figure 5.10 reveals that the straightness achieved by both the processes are almost identical.

Figure 5.10 Straightness of micro grooves for a length of 10 mm

Though the gravity assisted micro EDM has the capability of facilitating high aspect ratio machining, it does have some limitations that are mentioned in the following section.

5.1.4 Limitations of GAME

1. Both FAST EDM and GAME have been primarily developed for the fabrication of straight grooves. For making more complex shaped grooves such as involute, polynomial and other arbitrary shapes, one may need appropriately designed foil holders, which incorporate the desired geometry of the grooves.
2. Weight of the component is another limitation for GAME. As the component is directly attached to the spindle in GAME, the inertial effects limit the maximum weight of the workpiece. In the present study the component used weighs 25 grams which may be adequate for microsystem technology applications. However, Fast EDM is not constrained by this limitation.
3. To implement GAME in a normal micro EDM machine using pin electrodes, major/permanent design changes will be required. The spindle needs to be immersed in the dielectric tank and the work holding mechanism also needs to be changed.

Hence, it will be preferable to invent a flushing technique which can be readily implemented in an existing machine that uses a pin electrode. The magnetic field assisted micro EDM, explained in the next section is an attempt in this direction.

5.2 Magnetic field assisted micro EDM

5.2.1 Introduction

The flushing technique discussed in section 5.1 is useful in the spark erosion of microgrooves. However the setup does not lend itself to wide variety of components as mentioned in section 5.1.4. The magnetic field assisted micro EDM is another novel flushing technique that is complementary to the GAME and is suitable for general purpose micro EDM machines where pin electrodes are predominantly used. This flushing method is based on the concept that a magnetic field can be applied to pull the loose debris during the machining of ferromagnetic materials. Verification of this concept is demonstrated in this section using a permanent magnet for which the pulling force is proportional to the magnetic field strength [193]. The estimated flux density and the approximate force exerted by various shapes of permanent magnets are given in Appendix F. The working principle and the experimental details are discussed in the following sections.

5.2.2 Working principle

A debris particle in magnetic field assisted micro EDM is subjected to two kinds of forces, namely the magnetic force, $\vec{F}_B$ and the centrifugal force, $\vec{F}_C$. The magnetic field produced by a bar magnet kept near a conducting material is shown in Figure 5.11. A particle kept in the magnetic field may be considered as a dipole.

Figure 5.11 Magnetic field produced by a bar magnet near a conducting material. The magnetic field lines leave from the north pole and enter the south pole

The magnetic force ($\vec{F}_B$) experienced by a dipole $\vec{\mu}$ placed in a non-uniform magnetic field $\vec{B}$ can be written as

$$\vec{F}_B = \nabla(\vec{\mu} \cdot \vec{B}) \quad (5.1)$$

where, $\nabla = \frac{\partial}{\partial x} \hat{i} + \frac{\partial}{\partial y} \hat{j} + \frac{\partial}{\partial z} \hat{k}$ is the gradient operator.

The intensity of the magnetic flux density ($\vec{B}$) is affected by the intensity of the magnetic field strength ($\vec{H}$) as shown in Equation 5.2.

$$\vec{B} = \mu \vec{H} \quad (5.2)$$

where, μ is the magnetic permeability of the substance.

The centrifugal force ($\vec{F}_C$) experienced by a debris particle of mass m is given by

$$\vec{F}_C = \frac{mv^2}{r} \quad (5.3)$$

where,

v = velocity of debris particle

r = radial distance of the particle from the axis of rotation of the electrode

The resultant force ($\vec{F}$) on the debris particle is given by the vector addition of the magnetic force and centrifugal force and is expressed in equation 5.4 and schematically shown in Figure 5.12.

$$\vec{F} = \vec{F}_B + \vec{F}_C \quad (5.4)$$

Figure 5.12 Force diagram. The resultant force ($\vec{F}$) acting on the debris particle is the vector addition of centrifugal ($\vec{F}_C$) and magnetic ($\vec{F}_B$) forces

This augmented resultant force will facilitate the transport of ferromagnetic debris particles out of the hole.

5.2.3 Experimental Work

The experimental setup is shown in Figure 5.13. A permanent magnet was used to establish a magnetic field in the machining zone. Using a tungsten tool electrode (ϕ 275 μm) micro holes were drilled on tool steel.

Figure 5.13 Experimental setup for machining of micro holes in a magnetic field

The machining parameters used in this study are given in Table 5.2 and the results obtained are shown in Figure 5.14.

Table 5-2 Machining parameters	
Electrode material	Tungsten rod (ϕ 275 μm)
Work material	Hardened tool steel XW 42
Magnetic field strength	0.13 Weber m^{-2}
Die electric	HL 25-S
Voltage	110 V
Revolution of electrode	3000 RPM
Capacitance	220 pF
Feed rate	30 $\mu\text{m s}^{-1}$

5.2.4 Results and Discussion

Magnetic field assisted micro electro discharge machining was carried out for several time intervals from 30 minutes to 360 minutes. Experiments were repeated three times randomly for each machining time. Figure 5.14 shows the hole depth (with deviations) obtained by measurements made for different machining time without magnet and with magnetic field.

Figure 5.14 Hole depth vs. machining time. The diameter of tool electrode is 275 μm and hole diameter is between 282 – 294 μm [194]

In the initial stages of the machining (i.e., in the first hour), there is no appreciable difference in the hole depth machined with and without the magnetic field. As the holes made in this period of time are relatively shallow with an aspect ratio of less than 1, the centrifugal force by itself is sufficient for the debris removal. However, with longer duration and deeper holes, the effect of the magnetic field becomes

clearer. The depth obtained with the magnetic field after 360 minutes of machining is $1177\text{ }\mu\text{m}$, which is about 26% more than the depth achieved without the magnetic field. Effective debris transportation was achieved due to the presence of the magnetic field. In the absence of debris, fresh work material is continuously being exposed for sparking and hence, larger hole depth is achieved.

The cross sectional images of the micro holes made with and without magnetic field are shown in Figure 5.15.

Figure 5.15 Presence of magnetic field increases the hole depth. Images are taken with OMIS optical microscope

Figure 5.15 reveals that there is no apparent difference in the straightness of the holes machined with and without magnetic field. The taper is less than 4 % for 90 % of the hole depth.

The surface finish of the holes made with and without magnetic field were studied by a *Talyscan 150* in non-contact mode using laser light. The result, shown in Figure 5.16, reveals that the side wall surface roughness values are marginally better for surfaces machined without the magnet field.

Figure 5.16 Comparison of surface roughness

The effect of the flushing techniques on material removal rate (MRR) and surface finish was studied with respect to the tool electrode material by conducting a set of experiments and the results are discussed in the following section.

5.3 Effect of flushing method vis-à-vis tool electrode material

The input and output factors used in this study are shown in Figure 5.17.

Figure 5.17 Input and Output parameters

The three tool electrode materials used are graphite, stainless steel and tungsten. The flushing techniques used are the magnetic and gravity assisted methods. FAST EDM, in which these two flushing methods are absent is represented as “*No flushing*” in Figure 5.17. For each parameter, the experiment was repeated five times and the results are discussed below.

5.3.1 Effect on MRR

The effect of the tool electrode material and flushing technique on the material removal rate is shown in Figure 5.18.

Figure 5.18 Material removal rate

The most conspicuous revelation of Figure 5.18 is the performance of graphite as tool electrode material. The MRR achieved using graphite is about 30 to 40 times more than that of the other two materials (tungsten and stainless steel). The reason for this outstanding performance of graphite can be understood by observing the way in which the material behaves during arcing[†]. This is discussed below.

[†] The multi-media file “*micro needle formation.wmv*” available in the accompanying CD ROM shows the micro needle like bridge forming phenomenon.

In micro EDM using foil electrodes, during arcing, the foil material melts and forms a short-circuit by establishing a bridge (the shape looks like a micro needle). During this period, the spindle automatically starts moving up. This withdrawal of spindle continues until the bridge is broken. Once the circuit becomes open, the spindle starts moving down towards the workpiece and the machining resumes. The entire time spent on the up and down motion of the spindle is wastage of machine time as no machining takes place during this period. When using the metal foils like tungsten and stainless steel, due to their ductile nature, the needle like bridge keeps stretching itself during the spindle retraction and does not sever so easily. Some times, the stretching may extend up to 2 mm before it severs. In the case of graphite which is brittle and shears away easily [195], no such “bridge formation” is noticed during arcing. After few μm upward movement of the spindle, machining resumes immediately. As the non-machining time is minimum, high MRR is achieved using graphite.

For tungsten and stainless steel, the MRR achieved in magnetic field assisted micro EDM is about 3 to 18% more than that of FAST and GAME. In the case of graphite electrode, GAME provides the maximum MRR. This method is preferable for other tool electrode materials too, when machining non-ferrous workmaterials, as the MRR achieved by GAME is about 4 to 10% more than that achieved by FAST EDM.

5.3.2 Effect on surface finish

The effect of the tool electrode material and flushing technique on the surface roughness is shown in Figure 5.19.

Figure 5.19 Surface roughness

From Figure 5.19, it can be seen that the surface finish achieved by GAME is slightly better than the other two methods. Among the tool electrode materials, the best surface finish is obtained when a tungsten electrode is used. Hence, it can be used in finishing operations, where material removal will be minimum. The surface roughness produced by stainless steel is marginally better than that of graphite. However, it has the advantage that it is readily available in thicknesses as small as $10\text{ }\mu\text{m}$. Moreover, stainless steel foil is much cheaper than the other two materials. Hence, it can be used for rough machining of micro grooves having thicknesses less than $200\text{ }\mu\text{m}$. For thicker grooves ($> 200\text{ }\mu\text{m}$), graphite can be used for rough machining. Tungsten, as discussed above can be used for finish machining.

5.4 Summary

The effects of the flushing methods and the tool electrode materials are summarised below:

1. Gravity assisted micro EDM provides better debris removal and this technique is highly useful for high aspect ratio machining.
2. The surface finish achieved by gravity assisted micro EDM is slightly (about 5 to 10%) better than the roughness values obtained with FAST EDM.
3. To incorporate gravity assisted micro EDM technique on a machine using standard pin electrodes, considerable design changes are necessary in the machine tool.
4. Magnetic field assisted micro EDM is a flushing technique complementary to GAME and can be readily applied to the existing micro EDM machine without any design changes.
5. The presence of a magnetic field in the machining zone improves the debris removal and hence, the aspect ratio of micro holes. The hole depth achieved in the present study is about 25% higher when compared to the conventional micro EDM process under similar working conditions. The effect of the magnetic field is more pronounced as the hole depth increases. Exhaustive studies involving various magnetic materials, strengths and shapes are needed for further understanding and improvement of this novel process.
6. Presence of a magnet increases the stray capacitance. Since micro EDM uses RLC circuit, the discharge energy is affected by the increase in stray capacitance which in turn affects the surface roughness as shown in Figure 5.16. Using ceramic magnets is a possible solution for this problem.

7. An obvious limitation of magnetic field assisted micro EDM is that it can be applied only during the machining of ferromagnetic work materials.
8. Among the tool electrode materials considered, graphite provides the maximum MRR and tungsten gives the best surface finish. Hence, these two materials can be used for roughing and finishing operations respectively. Since the minimum thickness of commercially available graphite foil is about 100 μm , roughing of thinner grooves can be done by using stainless steel foils.

In this chapter, the principles of novel flushing techniques and the effect of these techniques and tool electrode materials on the MRR and surface finish were discussed. A comparison of key results using foil electrodes for different methods of machining is given in Table 5.3.

Table 5-3 Comparison of key results using foil electrodes

	FAST	GAME	Magnetic
Tool electrode material	Tungsten Stainless steel Graphite	Tungsten Stainless steel Graphite	Tungsten Stainless steel Graphite
Work material	Tool steel (XW 42)	Tool steel (XW 42)	Tool steel (XW 42)
Material removal rate ($\mu\text{m/hr}$)	16.0 (using W) 10.3 (using SS) 468 (using graphite)	16.7 (using W) 11.1 (using SS) 529 (using graphite)	17.2 (using W) 12.2 (using SS) 507 (using graphite)
Surface finish R_a (μm)	0.31 (using W) 0.89 (using SS) 0.98 (using graphite)	0.31 (using W) 0.82 (using SS) 0.89 (using graphite)	16.0 (using W) 10.3 (using SS) 468 (using graphite)
Aspect ratio	2.3	7.95	3.99
Electrode wear ratio	3.48	2.51	3.12
Straightness of the groove	< 18 μm / 10 mm	< 18 μm / 10 mm	< 20 μm / 10 mm

The thermal effect of the spark erosion process on the work material is studied in the next chapter by conducting numerical studies using finite element method and experimental verification by AFM and nanoindentation techniques.

Chapter 6

Numerical study and process simulation

As micro EDM is a thermal process, it leaves residual stress on the workpiece. It is essential to estimate the residual stress due to spark erosion as it reduces the fatigue strength of electro-discharge machined components. The thermal effects of micro EDM on the work material were studied using the finite element method in which a single spark erosion is considered. This chapter consists of three parts. It begins with the details of the FEM study. The experimental details of crater making and verification of the simulated results by the nanoindentation technique is explained in the next section. The results obtained are discussed in the final section.

6.1 Details of the FEM study

In the following sections the physical description of the process, the idealistic and simplifying assumptions made, the mathematical modeling of the process and the numerical implementation of the same, using commercially available finite element software are described. The ANSYS input listing of the commands used for the modeling and simulation are given in Appendix G and H.

6.1.1 Physical description

A three dimensional model of micro electro discharge machining as shown in Figure 6.1 was studied. The symmetrical nature of the process has been exploited and only a quarter of the model was analysed. Due to the thermal nature of the process, the energy balance equation governing the process has been solved with appropriate thermal initial and boundary conditions.

The following simplifying assumptions have been made in this study.

1. The workpiece is defect free and is made of homogeneous and isotropic material.
2. Temperature dependent material properties [196] of the workpiece material Ti6Al4V shown in Table 6.1 - 6.4 are used. Properties for the intermediate temperatures are determined by linear interpolation.
3. Internal stresses are absent in the workpiece before the micro EDM process.
4. The yield stress of the workpiece in tension is the same as that in compression.
5. Heat transfer is by conduction within the workpiece and by convection at the workpiece-dielectric liquid interface.
6. Only one spark is considered for the analysis.
7. The capacitor is fully charged and discharged during the process.

Figure 6.1 Three dimensional thermal model of the micro EDM. Surfaces Γ_2 and Γ_5 are the planes of symmetry. Thermal loading is applied on Γ_1 . The corresponding hidden surfaces in the opposite side are $\Gamma_4, \Gamma_3, \Gamma_6$

Table 6-1 Temperature dependent thermal conductivity

Temperature (°C)	Conductivity (W/m K)
20	6.6
93	7.3
205	9.1
315	10.6
425	12.6
540	14.6
650	17.5

Table 6-2 Temperature dependent specific heat

Temperature (°C)	Specific heat (J/kg K)
20	580
205	610
425	670
650	760
870	930

Table 6-3 Temperature dependent thermal expansion coefficient

Temperature (°C)	β ($10^{-6}/\text{K}$)
0	8.6
200	9.5
400	9.7
600	10.6

Table 6-4 Temperature dependent elastic modulus

Temperature (°C)	Young's modulus (GPa)
0	105
200	94.7
400	84.1
600	74.2
800	62.8

6.1.2 Mathematical description

This section covers the mathematical equation governing the heat transfer model, the energy equations for the micro EDM process, types of thermal load and heat fluxes considered, the method of determining the spark radius and the initial and boundary conditions of the mathematical model.

6.1.2.1 Governing equation

The three dimensional thermal diffusion equation governing the heating of the workpiece during single spark is given by [197]

$$\nabla^2 T = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (6.1)$$

where, the symbols are defined in the Nomenclature.

Considering the temperature dependent material properties, the governing equation in spatial and temporal coordinates in a domain Ω is given by

$$\frac{\partial \left(k_x \frac{\partial T}{\partial x} \right)}{\partial x} + \frac{\partial \left(k_y \frac{\partial T}{\partial y} \right)}{\partial y} + \frac{\partial \left(k_z \frac{\partial T}{\partial z} \right)}{\partial z} + Q = \rho \frac{\partial CT}{\partial t} \quad (6.2)$$

6.1.2.2 Energy calculations

The discharge energy in the micro EDM (neglecting stray capacitance) is given by

$$E_d = \frac{1}{2} C_d V_d^2 \quad (6.3)$$

Considering a spark on time (t_{on}), the total heat flow rate (Q) is given by

$$Q = \frac{E_d}{t_{on}} \quad (6.4)$$

Most of this heat is taken away by the dielectric liquid and cathode. The portion available for anode absorption, is given by

$$Q_a = \eta Q \quad (6.5)$$

The value of η is taken as 0.08 as suggested in reference [129].

6.1.2.3 Type of thermal load and heat flux

6.1.2.3.1 Concentrated point heat load

This type of loading is based on a simple physical idea that a finite quantity of heat is instantaneously released at a given point and time in an infinite solid body. In the FEM simulation, heat applied with prescribed rate (Q_p) at a single point in the workpiece over a period of time t is integrated with respect to time. This type of loading is generally not preferable due to singularity problems. Moreover, due to the extremely fine finite element meshing required at the loading zone the analysis will be time consuming and expensive. In the present study, this analysis is done as a preliminary step to simulate the crater due to single spark erosion. Since the spark radius is equivalent to the crater radius [32, 128], the radius value obtained is used as spark radius (r_s) in the subsequent Gaussian type of loading. Since a quarter of the workpiece is studied due to symmetry, the heat rate for the point loading is given by

$$Q_p = \frac{1}{4} Q_a \quad (6.6)$$

6.1.2.3.2 Gaussian distribution of heat flux

The Gaussian-distributed heat source is a simplified model for the local concentration of heat input when its density is assumed to follow the Gaussian distribution. Normally, the temperature field in the vicinity of the heat source is particularly dependent on the heat-flow density of the heat source. However, the temperature at the far field is less sensitive to the heat-flow density. Therefore, the distributed heat source gives a similar temperature distribution if the heat source is replaced by a concentrated point source in the centre of its area. Hence, a Gaussian-distributed heat source can be used to get a better prediction of the temperature field

near the source centre to overcome the weakness of the point heat source, which would predict an infinitely high temperature at the source location.

The heat flux density rate (q_r) at a distance r from the origin in Gaussian-distributed heat source is given by [198]

$$q_r = q_{\max} e^{-k \left(\frac{r}{r_s} \right)^2} \quad (6.7)$$

where, $q_{\max}$ is the maximum heat flux density rate (at $r = 0$).

The distribution parameter k in Equation 6.7 is the coefficient that determines the concentration of the heat source. The value of k varying from 1 to 4.5 has been used for the EDM process [141-143]. A middle value of 3 (which is also used in other manufacturing processes [199-202]) is used in this study.

The value of $q_{\max}$ can be expressed in terms of q , by comparing the total heat absorbed by the anode with a uniform distribution with that of the Gaussian distribution.

The total heat absorbed by the anode with a uniform distribution is given by

$$Q_a = q \pi r_s^2 \quad (6.8)$$

The expression for the total heat absorbed by the anode with a Gaussian distribution is derived using Figure 6.2 as below.

Considering a small annulus ring of thickness dr at a radial distance r from the origin, the heat absorbed by this annulus ring is given by

$$Q_r = q_r 2\pi r dr \quad (6.9)$$

where

$$q_r = q_{\max} e^{-3 \left(\frac{r}{r_s} \right)^2} \quad (6.10)$$

Substituting Equation 6.10 in Equation 6.9,

$$Q_r = q_{\max} e^{-3\left(\frac{r}{r_s}\right)^2} 2\pi r dr \quad (6.11)$$

The total heat absorbed by the anode with a Gaussian distribution can be obtained by integrating Equation 6.11 between the limits $r = 0$ and $r = r_s$

$$Q_a = \int_0^{r_s} q_{\max} e^{-3\left(\frac{r}{r_s}\right)^2} 2\pi r dr \quad (6.12)$$

Figure 6.2 Schematic representation of Gaussian heat flux distribution

Equation 6.12 is solved in the following manner:

$$\text{Let } t = -3 \frac{r^2}{r_s^2} \quad (6.13)$$

$$\text{then, } dt = \frac{-6r dr}{r_s^2} \quad (6.14)$$

Substituting Equation 6.13 and 6.14 in Equation 6.12 and changing the limits,

$$Q_a = \frac{-\pi q_{\max} r_s^2}{3} \int_0^{-3} e' dt \quad (6.15)$$

$$Q_a = \frac{\pi q_{\max} r_s^2}{3} (1 - e^{-3}) \quad (6.16)$$

Since the total heat absorbed at the anode is constant, Equation 6.16 can be equated with Equation 6.8.

$$Q_a = \frac{\pi q_{\max} r_s^2}{3} (1 - e^{-3}) = q \pi r_s^2 \quad (6.17)$$

On simplification,

$$q_{\max} = 3.1572 q \quad (6.18)$$

6.1.2.4 Spark radius

The spark radius (r_s) mentioned in Equation 6.7 is a time variable [129] and is given by

$$r_s = \kappa t^{\frac{3}{4}} \quad (6.19)$$

Since a good estimate of the constant κ for the micro EDM is not available, the value of spark radius (r_s) is assumed constant and is obtained as mentioned in section 6.1.2.3.1

6.1.2.5 Initial condition

The initial temperature T_i of the workpiece is equivalent to the ambient (bulk) temperature T_o of the dielectric liquid in which the workpiece is immersed in the tank. Hence,

$$T_i = T_o \text{ at } t = 0 \quad (6.20)$$

6.1.2.6 Boundary condition

The domain (Ω) of the study is a 50 X 50 X 20 μm rectangular block as shown in Figure 6.3. Since quarter symmetry is considered, adiabatic boundary conditions are applied on the two planes of symmetry.

$$\frac{\partial T}{\partial x} = 0 \text{ on } \Gamma_5 \text{ and } \frac{\partial T}{\partial y} = 0 \text{ on } \Gamma_2 \quad (6.21)$$

On the top surface convective heat transfer takes place between the workpiece and the dielectric liquid during spark off time. During sparking, energy is supplied to the workpiece within the area covered by the spark radius (r_s). On the area beyond this spark zone heat is lost to the dielectric liquid.

$$\left. \begin{array}{l} K \frac{\partial T}{\partial z} = h_c (T - T_0) \quad \text{for spark off time} \\ K \frac{\partial T}{\partial z} = q \text{ if } r \leq r_s \\ K \frac{\partial T}{\partial z} = h_c (T - T_0) \text{ if } r \geq r_s \end{array} \right\} \begin{array}{l} \text{for spark on time} \\ \text{on } \Gamma_1 \end{array} \quad (6.22)$$

Since the problem domain is very small and the other three surfaces Γ_3 , Γ_4 and Γ_6 are at such distance far away from the corresponding physical walls, no heat transfer takes place across them.

$$K \frac{\partial T}{\partial x} = K \frac{\partial T}{\partial y} = K \frac{\partial T}{\partial z} = 0 \text{ on } \Gamma_3, \Gamma_4 \text{ and } \Gamma_6 \quad (6.23)$$

6.1.3 Numerical description

Using finite element techniques, a system with an infinite number of unknowns can be transformed into one that has finite number of unknowns, related to each other by elements of finite size. In this study a commercially available finite element code (ANSYS 7.0 University High) has been used for this purpose. The geometry and the mesh of the system is shown in Figure 6.3.

Figure 6.3 Geometry and mesh. Dimensions are 50 X 50 X 20 μm

Transient thermal analysis is done to obtain the thermal history of the system during the micro EDM process. Integration of the heat conduction equation with respect to time is performed by transient thermal analysis. The heat conduction equation for each element, in the finite element formulation, can be written as

$$[C(T)]\{\dot{T}\} + [K(T)]\{T\} = \{Q(T)\} \quad (6.24)$$

A Newton-Raphson iterative process is used to solve Equation 6.24 at discrete time points (using an automatic time step feature) within the transient. The ambient temperature is specified as the initial (starting) temperature and subsequent temperatures are calculated by iteration. The iterative process continues until a converged solution is achieved. The solution data, such as nodal temperature, can be obtained in graphical as well as in tabular form for subsequent analyses. The results obtained from the thermal analysis are used as input for the structural analysis. With appropriate boundary conditions, the stress distribution within the workpiece is obtained. The simulation parameters are shown in Table 6.5.

Table 6-5 Simulation parameters

Analysis type	Three dimensional thermal transient
Element used	3D Brick element (Solid 90)
Nodes per element	20
Iterative method	Newton-Raphson
Time step	Automatic
Meshing type	Mapped meshing
Spark radius	2.1 μm
Convection heat transfer coefficient	10000 ($\text{W m}^{-2} \text{K}^{-1}$)
Work material	Ti6Al4V
Initial temperature	20 $^{\circ}\text{C}$
Workpiece size	10 X 10 X 2 mm
FEM domain size	50 X 50 X 20 μm
Capacitance	3300 pF
Discharge voltage	110 V
Spark <i>On-time</i>	100 ns

The value of spark radius is obtained as discussed in section 6.1.2.3.1. The simulated crater shape using a point thermal load is shown in Figure 6.4. The Spark-*On-time* is obtained as discussed in section 3.2.6.

Figure 6.4 Spark radius value obtained by FEM simulation using point thermal load

6.1.4 Residual stress estimation

During the sparking, the workpiece is locally heated and is subjected to extreme temperature gradients. Due to the non-uniform temperature distribution during the thermal cycle, local thermal expansion of the workpiece causes thermal stresses. This and the associated metallurgical transformation due to melting and solidification, result in residual stresses in the workpiece. The transient thermal distribution obtained from the thermal analysis is used as an input for the calculation of the thermal stresses. The stress-strain relationship due to temperature variation is given by the thermo-elastic stress-strain equation

$$\{\dot{\sigma}\} = [D]\{\dot{\epsilon}\} - \{\dot{m}\} \quad (6.25)$$

The experimental verification of the residual stress estimation is done by nanoindentation. The concept of residual stress measurement using nanoindentation

is based on the fact that penetration depth of the indenter is affected by the stress field of the specimen. At a constant load, the penetration depth of each nanoindentation will depend on the distance from the crater center. Based on the load-displacement data, physical properties such as Young's modulus and hardness are obtained for the workpiece harboring the residual stresses. These values are compared with the values obtained for an unstressed specimen and using equation 6.26, the residual stress is calculated [172].

$$\sigma_r = \frac{K_C}{(\pi d_{f*})^{\frac{1}{2}}} \left[1 - \left(\frac{E_* H_0}{E_0 H_*} \right)^{\frac{1}{2}} \left(\frac{d_{of}}{d_{f*}} \right)^{\frac{3}{2}} \right] \quad (6.26)$$

where,

K_C = constant based on the material toughness.

E_* = Young's modulus of the crater zone

H_* = hardness value of the crater zone

d_{f*} = penetration depth of the crater zone

E_0 = Young's modulus of the bulk material

H_0 = hardness value of the bulk material

d_{of} = penetration depth of the bulk material.

6.2 Experimental Work

6.2.1 Specimen preparation

Commercially available Ti6Al4V plate of size 10 X 10 X 2 mm is used for the experiment. As fine surface finish is required for the proper identification of crater during AFM and nanoindentation studies, grinding and polishing of the specimen are done as per the standard operation procedure for metallographic specimen preparation. Wet grinding of specimen is done using BUEHLER HANDIMET2®

Roll grinder. The details of the SiC abrasive grinding paper rolls used are mentioned in Table 6.6.

Table 6-6 Abrasive paper roll specification

FEPA P Standard	Grit #P180	Grit #P400	Grit #P800	Grit #P1000
US Standard	180	320	400	600
Grain particle size (μm)	76	35	22	18

After grinding, polishing is done with 6, 3 and 1 μm diamond particle size using a synthetic cloth on BUEHLER ECOMET6[®] variable speed Grinder-polisher.

6.2.2 Crater formation

A micro EDM system, MG-ED72W, with standard set-up is used for the crater formation. For the crater formation, the tool electrode was ground to a very small diameter (3 μm) by the built-in wire-grinding unit and used as a cathode. The CNC program used for the wire grinding is given in Appendix E. The machining parameters used for the wire electro discharge grinding (WEDG) are given in Table 6.7.

Table 6-7 Machining parameters for WEDG

Electrode material	Tungsten rod
Work material	Polished Ti6Al4V
Die electric	HL 25-S
Voltage	70 V
Rotational speed of the electrode	3000 RPM
Capacitance	10 pF
Feed rate	10 $\mu\text{m s}^{-1}$

A JEOL scanning electron microscope (SEM) was used for the imaging of the machined surfaces and the ground electrode as shown in Figure 6.5.

Figure 6.5 Scanning electron microscope image of the micro electrode used for crater formation. The electrode tip is shown separately at the top left portion. Magnification of the tip is X4500

Using this electrode a crater was made on the workpiece. The parameters used for crater machining are given in Table 6.8.

Table 6-8 Machining parameters for crater formation

Electrode material	Tungsten rod
Work material	Polished Ti6Al4V
Die electric	HL 25-S
Voltage	110 V
Revolution of electrode	3000 RPM
Capacitance	3300 pF
Feed rate	$30 \mu\text{m s}^{-1}$

6.2.3 Nanoindentation

Nanoindentation was carried out on a polished sample (sample before spark erosion) to get the physical (reference) values and then the experiment was repeated on the micro spark eroded specimen using Nano-Indenter XP system. The load used for the nanoindentation was 1000 μN . A total of 100 indentations were made on polished sample and 64 indentations were made in crater region. Geometric configurations of the indents are shown in Figure 6.6 and 6.7.

Figure 6.6 Geometric configuration of indents on polished surface

Figure 6.7 Geometric configuration of indents on the crater region

The bulk material properties of the polished surface were calculated by averaging the values obtained by nanoindentation at 100 points. These values are given in Table 6.9

Table 6-9 Bulk material properties of polished Ti6Al4V material

Property	Value	Unit
Young's Modulus	157	GPa
Hardness	6.96	GPa
Depth	82.3	nm
Toughness	75	MPa-m ^{1/2}

The Young's modulus, microhardness and penetration depth for the crater region are shown in Figure 6.8.

Figure 6.8 Nanoindentation data for crater region

The values shown in Table 6.9 and Figure 6.8 are used in Equation 6.26 to calculate the residual stresses.

6.3 Results and Discussion

6.3.1 Crater formation

The crater simulated by the finite element technique is shown in Figure 6.9. The crater simulated has a diameter of $6.3\text{ }\mu\text{m}$ and a diameter to depth ratio of 3.45.

Figure 6.9 Crater shape simulated by FEM . The diameter to depth ratio is 3.45

The workpiece was examined using an AFM. The results obtained are shown in Figure 6.10. The measured value of diameter is $3.482\text{ }\mu\text{m}$ and the diameter to depth ratio is 3.99.

Figure 6.10 Crater shape measured by AFM. The diameter to depth ratio is 3.99 [203]

Considerable difference is noticed between the crater dimensions by simulation and by AFM measurement. This is due to the fact that in simulation single spark is assumed, whereas in practice, invariably multi sparking occurs. Another reason for the difference is that in the simulation, it is assumed that all the material above the melting point is removed from the workpiece. This is done using the “*Element Death*” option available in the software. The software is programmed to select those elements above the temperature 1922 K (melting point of Ti6Al4V). These elements are considered as “*Dead*” and only the “*Live*” elements are shown. But in practice, only a portion of the molten metal (10 – 15% [204]) during sparking will be removed as debris and balance will solidify to form a recast layer on the parent material. Hence, the measured dimensions of the crater is much less than the simulated value.

6.3.2 Temperature history and Distribution

From the transient thermal analysis performed, the temperature variation over a period of time can be simulated. The temperature history of a point on the top surface at a radial distance of $1.5\text{ }\mu\text{m}$ and that of a point at a depth of $1.5\text{ }\mu\text{m}$ from the top surface, as shown in Figure 6.11 are given in Figure 6.12. Figure 6.13 shows the variation of temperature along the radial and axial directions.

Figure 6.11 Location of the two points considered for temperature history

Figure 6.12 Temperature history

The simulated temperature values shown in Figure 6.12 indicate that the thermal rise is more rapid on the top surface. The temperature on the top surface at a radial

distance of $1.5\ \mu\text{m}$ from the centre reaches $5000\ \text{K}$ in less than $3\ \text{ns}$, whereas, to reach this temperature, it takes about $100\ \text{ns}$ for a point at the same distance beneath the top surface.

Figure 6.13 Temperature distribution

From Figure 6.13 it can be seen that the material within a radial distance of $3\ \mu\text{m}$ from the centre experiences a temperature above the melting temperature and material beyond $4.5\ \mu\text{m}$ remains at bulk temperature, unaffected by sparking. For a point at a depth of $1.5\ \mu\text{m}$ beneath the top surface, the corresponding distances are 2 and $3\ \mu\text{m}$ respectively. Experimental verification of spatial and temporal temperature distribution is an extremely difficult task. Temperature measurement involving a turbulent oil-plasma interaction as in micro EDM is a research challenge by itself and is beyond the scope of the present work. However, these simulations do suggest that the thermal effect on the material is more pronounced on the top surface. As seen in section 2.2.3 of the literature review, nanoindentation is a very good technique to study such surfaces with nanometric precision. This technique can be used to determine the stresses induced by the sparking as discussed in the following section.

6.3.3 Residual stress estimation

Residual stresses simulated by the finite element method for the Gaussian heat source is shown in Figure 6.14.

Figure 6.14 Distribution of the von Mises stress in the sparking zone by simulation

Comparison of the simulated stress and stress measured by nanoindentation is given in Figure 6.15.

Figure 6.15 Comparison of residual stresses

From the figure it can be seen that the simulated stress value is above the ultimate tensile strength (860 MPa) of the material near the spark centre and gradually diminishes as the distance from the centre increases. The stress values measured by nanoindentation of the spark eroded surface are below 300 MPa. These values are less than the simulated stress values within a distance of 10 μm from the spark centre. This deviation is possibly due to the stress relaxation caused by the surface micro cracks formed during the spark erosion.

6.4 Summary

The finite element method was used to simulate crater formation due to a single spark by micro electro discharge machining of Ti6Al4V alloy. The crater shape was measured by AFM and found to have a diameter and depth of 3.48 μm and 0.87 μm respectively. This is less than the simulated values of 6.3 μm and 1.83 μm respectively. The AFM values are the final dimensions of the crater after the recast of a some molten metal where as the simulated values do not include the recasting of molten material. The residual stresses on and near the crater were estimated using the FEM. The estimated residual stress values were compared with the residual stress values obtained experimentally using nanoindentation technique. This study reveals following points:

1. The thermal effect of micro EDM is more pronounced on the top surface than the bulk material beneath the surface.
2. The residual stresses induced are found to be less than 300 MPa. This value is well below the ultimate tensile strength of the material.

Chapter 7

Conclusions and future work

7.1 Conclusions

Conclusions made from the present research work are as follows:

1. Micro foil is used for long straight groove machining. Groove length of 25 mm has been successfully made in the present work with a straightness value of 18 μm (for a length of 10 mm).
2. By sparking beneath the component, gravitational force is effectively utilized for debris removal. It is especially useful for high aspect ratio machining. An aspect ratio of 8 is achieved by this technique in the machining of tool steel workmaterial using graphite tool electrode.
3. Magnetic field is effectively used in debris removal during the spark erosion of ferrous materials. Using this technique an improvement of about 25% in hole depth is achieved in the present study as compared to the conventional micro EDM process under similar working conditions. This demonstrates the advantage of this technique, particularly in high aspect ratio machining.
4. Among the foil materials, graphite gives the highest material removal rate. It also wears out rapidly. Hence, it can be used for roughing. Tungsten foil displays a 'no-wear' like characteristic and can be used for finishing work. Since, it is difficult to handle graphite foils with thickness less than 100 μm , roughing work involving groove thickness less than 100 μm , is done using stainless steel foils.

5. Simulation of the micro EDM process using finite element method and experimental results by nanoindentation of micro spark eroded surface shows residual stress values below 300 MPa.

7.2 Future work

Application of the magnetic field as a flushing method in the micro electro discharge machining process is explored in the present work. Simulation studies involving permanent magnets having various shapes and field strength will be useful to fully exploit the process. Another possible application of the magnetic field is in proper control of the flow of ions in micro EDM. Focusing of charged particles with quadruple magnets in micro EDM can be useful in

1. High aspect ratio machining
2. Electro discharge finishing (or polishing)

The hypothesis is that, by converging the ions at a particular spot, the intensity (energy) can be substantially increased and this can be used for high aspect ratio (narrower and deeper) machining. On the other hand, by diverging the ions to a wider area, the available energy per unit area can be brought down. This is likely to produce comparatively shallow craters and hence, there is a possibility of better finish of the spark eroded surfaces.

Other future works, possible out of this present study are

1. Process simulation in multi-physics environment using finite element method. Study of crater formation due to multi-sparking and incorporation of plasma flushing efficiency factor in the crater shape determination are useful for the development of hybrid machining processes.
2. Study of material accretion on a substrate by micro EDM using foil electrode as shown in Figure 7.1

Figure 7.1 Electro discharge material deposition

3. Batch machining of micro grooves using multiple foils.
4. Micro groove machining of complex shapes using appropriate foil holders.
5. In addition to the dimension and surface roughness measurements done in the present study, further analysis of surface texture need to be carried out to relate the surface features to process parameters.

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Appendix A

Commercial sources of materials used

The details of the commercial material suppliers of the materials used in the present work are given below.

Material	Supplier	URL
Tungsten foil, Brass, Ti6Al4V	Goodfellow	http://www.goodfellow.com
Graphite foil	Poco graphite	http://www.poco.com
Stainless steel foil	Hasberg-Schneider GmbH	http://www.hasberg-schneider.de/english/index.html
Tungsten rod	NTP Technology Pte Ltd	http://www.ebizasialink.com/e-StoreFront/ntp/
Tool steel	Assab Steels	http://www.assabsteels.com
Permanent magnet	Alniff Industrial Pte.Ltd	http://www.alniff.com.sg/

In addition to the above mentioned suppliers, an exhaustive list of material suppliers can be found in following links

<http://metals.about.com/od/suppliersbyname/>

<http://www.azom.com>

<http://www.matweb.com/reference/link.asp>

Appendix B

CNC Program for FAST EDM

The computer numerical control (CNC) program (written in BASIC language) used for the micro EDM is given below:

```
'  
  
'   MG-ED72 DEMO PROGRAM  
  
'   REMOTE COMMAND  
  
'   ( REMOTE.BAS )  
  
'  
  
DECLARE SUB MACHINING ()  
  
DECLARE SUB oput (MCODE AS STRING)  
  
'MAIN  
  
    CLS  
  
    OPEN "COM1: 9600,N,8,1,ASC,LF" FOR RANDOM AS #1  
  
    CALL MACHINING  
  
    CLOSE #1  
  
    END  
  
SUB MACHINING  
  
    DIM DCODE AS STRING  
  
'----- INITIAL -----  
  
    CALL oput("buz 2")  
  
    CALL oput("back x 10")
```


CALL oput("back y 10")

CALL oput("spn 1")

CALL oput("fsf z 30")

CALL oput("fsm z 30")

CALL oput("fsf x 150")

CALL oput("fsf y 150")

CALL oput("con 1")

CALL oput("vol 2 110")

CALL oput("vol 0")

CALL oput("res x")

CALL oput("res y")

'----- MACHINING -----'

CALL oput("ABS X 0")

CALL oput("ABS Y 0")

CALL oput("MCV y 50099 50099 100000")

'----- ALL RESET -----'

CALL oput("fsf z 100000")

CALL oput("abs z -350000")

CALL oput("spn 1")

CALL oput("vol 1")

CALL oput("buz 2")

END SUB

SUB oput (MCODE AS STRING)

 DIM ANSCODE AS STRING

 PRINT " OUTPUT CODE = ", MCODE'

 PRINT #1, MCODE

 INPUT #1, ANSCODE

 PRINT " RETURN CODE = ", ANSCODE

END SUB

Appendix C

CNC Program to incorporate Table movement

In order to incorporate the table movement during machining, a slot machining code was used instead of the hole machining code. The changes made (under the heading MACHINING in the program given in Appendix B) are given below:

Original Code:

```
CALL oput("MAC 10000")
```

Revised Code:

```
CALL oput("MCV y 500 500 10000")
```

Appendix D

CNC Program for GAME

Following additional changes are made in the CNC program (under the heading INITIAL in the program given in Appendix B) to retain the polarity of the workpiece as anode and the polarity of the tool electrode as cathode :

The changes made are given below:

Original Code:

CALL oput("vol 2 110")

Revised Code:

CALL oput("vol 2 -110")

Appendix E

CNC Program for WEDG

The CNC program used for the micro wire electro discharge grinding (WEDG) is given below:

```
DECLARE SUB Dcut ()
DECLARE SUB MACHINING ()
DECLARE SUB MRESET ()
DECLARE SUB OPUT (MCODE AS STRING)
DECLARE SUB XABS (XO AS DOUBLE)
DECLARE SUB YABS (YO AS DOUBLE)

DIM SHARED TOOLRADIUS(7) AS DOUBLE
DIM SHARED ZLENGTH(7) AS DOUBLE
DIM SHARED CAPACITOR(7) AS INTEGER
DIM SHARED VOLTAGE(7) AS DOUBLE
DIM SHARED MSPEED(7) AS DOUBLE
DIM SHARED FSPEED(7) AS DOUBLE
DIM SHARED FILECOUNT AS INTEGER
DIM SHARED XWEDGORG AS DOUBLE
DIM SHARED YWEDGORG AS DOUBLE
DIM SHARED Xoffset AS DOUBLE
DIM I AS INTEGER

'MAIN

    DIM ANSCODE AS STRING

    XWEDGORG = -215870
```

YWEDGORG = -50000

Xoffset = 25

' Total Step

' X Z C V FSM FSF

DATA -500,2000,1,110,30,200

DATA 50,1200,1,100,20,1200

DATA 20,1000,2,90,20,1000

CLS

FILECOUNT = 3

FOR I = 1 TO FILECOUNT

READ TOOLRADIUS(I), ZLENGTH(I), CAPACITOR(I), VOLTAGE(I), MSPEED(I),

FSPEED(I)

NEXT I

OPEN "COM1:9600,N,8,1,ASC,LF" FOR RANDOM AS #1

CALL OPUT("BUZ 2")

CALL MACHINING

' CALL Dcut

PEND:

CALL MRESET

E:

END

SUB Dcut

```
CALL OPUT("FSF Z 500")
CALL OPUT("FSM Z 10")
CALL OPUT("abs x " + STR$(XWEDGORG + 150))
CALL OPUT("SPN 1")
CALL OPUT("VOL 2 110")
CALL OPUT("CON 1")
CALL OPUT("CUA Z 5000 X 0 0")
CALL OPUT("FSF Z 10000")

END SUB
```

```
SUB MACHINING          'KAKOU-Program
```

```
    DIM DCODE AS STRING
```

```
    DIM I AS INTEGER
```

```
    DIM T AS INTEGER
```

```
    CALL OPUT("BACK X 10")
```

```
    CALL OPUT("BACK Y 10")
```

```
    CALL OPUT("FSF X 10000")
```

```
    CALL OPUT("FSF Y 10000")
```

```
    CALL OPUT("WIRE 1")
```

```
    CALL OPUT("SPN 0")
```

```
"TANMEN-KAKOU
```

```
    FOR I = 1 TO 1
```

```
        DCODE = "ABS X " + STR$(TOOLRADIUS(I) + Xoffset + XWEDGORG):
```

```
    CALL OPUT(DCODE)
```

```
        CALL YABS(YWEDGORG)
```

```
        DCODE = "FSF Z " + STR$(FSPEED(I)):          CALL OPUT(DCODE)
```

```
        DCODE = "FSM Z " + STR$(MSPEED(I)):          CALL OPUT(DCODE)
```

```
        DCODE = "CON " + STR$(CAPACITOR(I)):      CALL OPUT(DCODE)
        DCODE = "VOL 2 " + STR$(-VOLTAGE(I)):      CALL OPUT(DCODE)
        DCODE = "MAP " + STR$(ZLENGTH(I)):        CALL OPUT(DCODE)
        FOR T = 1 TO 1000
        NEXT T
        DCODE = "RES Z":                          CALL OPUT(DCODE)
        DCODE = "ABS Z -100":                      CALL OPUT(DCODE)
    NEXT I

'ARA-KAKOU & SHIAGE-KAKOU
    FOR I = 2 TO FILECOUNT
        DCODE = "ABS X " + STR$(TOOLRADIUS(I) + Xoffset + XWEDGORG):
        CALL OPUT(DCODE)
        CALL YABS(YWEDGORG)
        DCODE = "FSF Z " + STR$(FSPEED(I)):        CALL OPUT(DCODE)
        DCODE = "FSM Z " + STR$(MSPEED(I)):        CALL OPUT(DCODE)
        DCODE = "CON " + STR$(CAPACITOR(I)):        CALL OPUT(DCODE)
        DCODE = "VOL 2 " + STR$(-VOLTAGE(I)):        CALL OPUT(DCODE)
        DCODE = "CUA Z " + STR$(ZLENGTH(I) + 600) + " X 0 0":
        CALL OPUT(DCODE)
        DCODE = "FSF Z " + STR$(FSPEED(I)):        CALL OPUT(DCODE)
        ' DCODE = "FSF Z 2000":                    CALL OPUT(DCODE)
        FOR T = 1 TO 1000
        NEXT T
        DCODE = "VOL 2 " + STR$(-VOLTAGE(I)):        CALL OPUT(DCODE)
        DCODE = "ABS Z -100":                      CALL OPUT(DCODE)
    NEXT I

END SUB
```


SUB MRESET 'RESET-Program

 CALL OPUT("FSF Z 100000")

 CALL OPUT("INN Z -200000")

 CALL XABS(XWEDGORG)

 CALL YABS(YWEDGORG)

 CALL OPUT("SPN 1")

 CALL OPUT("WIRE 2")

 CALL OPUT("VOL 1")

 CALL OPUT("BUZ 2")

END SUB

SUB OPUT (MCODE AS STRING) 'Remote Command Output Program

 DIM ANSCODE AS STRING

 DIM nn AS DOUBLE

 PRINT MCODE

 PRINT #1, MCODE

 FOR nn = 1 TO 100: NEXT nn

 INPUT #1, ANSCODE

 PRINT ANSCODE

END SUB

SUB XABS (XO AS DOUBLE)

 DIM DCODE AS STRING

 DCODE = "ABS X " + STR\$(XO): CALL OPUT(DCODE)

END SUB

SUB YABS (YO AS DOUBLE)

 DIM DCODE AS STRING

 DCODE = "ABS Y " + STR\$(YO): CALL OPUT(DCODE)

END SUB

Appendix F

Empirical formulae for permanent magnets

The empirical formulae suggested by the *International Magnetics Association* for the design of common shapes of permanent magnets are given below.

Cylindrical Magnet

For a permanent cylindrical magnet (Radius R and Thickness T) having residual induction B_r , the estimated flux density B_x on the central axis at a distance x from the magnet is given by

$$B_x = \frac{B_r}{2} \left[\frac{x+T}{\sqrt{R^2 + (x+T)^2}} - \frac{x}{\sqrt{R^2 + x^2}} \right] \quad (F1)$$

Rectangular Magnet

For a permanent rectangular magnet (Length L , Width W and Thickness T) having residual induction B_r , the estimated flux density B_x on the central axis at a distance x from the magnet is given by

$$B_x = \frac{B_r}{\pi} \left[\tan^{-1} \frac{WL}{2x\sqrt{4x^2 + W^2 + L^2}} - \tan^{-1} \frac{WL}{2(x+T)\sqrt{4(x+T)^2 + W^2 + L^2}} \right] \quad (F2)$$

In the above mentioned formulae (F1 and F2), thickness T is replaced by $2T$ in the case of magnet on a steel back plate (because steel mirrors the magnet)

The empirical formula for the approximate estimate of the pulling force exerted by the magnet is given by

$$F = 0.577 B_x^2 A \quad (F3)$$

where,

F = force in pounds

B_x = flux density in Kilogauss

A = pole area in square inches

The pulling force shown in formula F3 is a function of the flux density in the area of interest. This flux density in turn is a function of residual induction and distance from the magnet as shown in formulae F1 and F2. Hence if greater pulling force is required, magnets with greater residual induction are to be used.

The residual induction of some of the permanent magnet materials are given below.

Material and Grade	Residual induction (Gauss)
Ceramic 1	2,200
Ceramic2	3,950
SmCo 18	8,600
SmCo 26	10,500
NdFeB 35	12,300
NdFeB 42H	13,300

Appendix G

ANSYS FEM simulation code for point thermal load

The ANSYS input code used for the modelling and simulation of the micro EDM using a concentrated (point) thermal load is given below:

```
/filename,point100

/title, Crater formed by point thermal load

/prep7

ET,1,SOLID90

blc4,0,0,50,50,-20

SMRTSIZE,3           !1=dense;5=coarse

MSHAPE,1,3D          !0=quad/hex;1=tri.teragonal

MSHKEY,0             !0=free;1=mapped meshing

VMESH,1

KREFINE,5, , ,2,1,1,1 !level 3 depth 1

KREFINE,5, , ,3,2,1,1 !level 2 depth 2

/VIEW, 1, -1, -1, 1

/ANG, 1, 60

/REPLO

MPTEMP,,,,,,,,

MPTEMP,1,0
```

```
MPDATA,DENS,1,,4428.78e-18

MPTEMP,,,,,,,,

MPTEMP,1,293,366,478,688,798,813

MPTEMP,7,923

MPDATA,KXX,1,,6.6e6,7.3e6,9.1e6,10.6e6,12.6e6,14.6e6

MPDATA,KXX,1,,17.5e6

MPTEMP,,,,,,,,

MPTEMP,1,293,478,698,923,1143

MPDATA,C,1,,580e12,610e12,670e12,760e12,930e12

MPTEMP,,,,,,,,

MPTEMP,1,273,473,673,873

MPDATA,ALPX,1,,8.6e-6,9.5e-6,9.7e-6,10.6e-6

MPTEMP,,,,,,,,

MPTEMP,1,77 ,273,473,673,873,1073

MPDATA,EX,1,,114.9e3,105e3,94.7e3,84.1e3,74.2e3,62.8e3

MPDATA,PRXY,1,,.23,.23,.23,.23,.24,.24

PHYSICS,WRITE,Thermal, , ,

PHYSICS,CLEAR

ETCHG,TTS

MPTEMP,,,,,,,,

MPTEMP,1,273,473,673,873

MPDATA,ALPX,1,,8.6e-6,9.5e-6,9.7e-6,10.6e-6

MPTEMP,,,,,,,,

MPTEMP,1,77 ,273,473,673,873,1073

MPDATA,EX,1,,114.9e3,105e3,94.7e3,84.1e3,74.2e3,62.8e3
```

MPDATA,PRXY,1,,23,23,23,23,24,24

MPTEMP,,,,,,,,

MPTEMP,1,0

MPDATA,DENS,1,,4428.78e-18

PHYSICS,WRITE,Struct, , ,

FINISH

/SOL ! Enter solution phase

PHYSICS,READ,Thermal

TUNIF,293 !INITIAL CONDITION !IC changed to TUNIF

SFA,2,,HFLUX,0 !BOUNDARY CONDITIONS

SFA,5,,HFLUX,0

SFA,1,,CONV,10000,293 !This is top surface

SFA,3,,HFLUX,0

SFA,4,,HFLUX,0

SFA,6,,HFLUX,0

antype,4 ! Transient analysis

SOLCONTROL, ON

time,100e-9 ! Time at end of analysis

nropt,full ! Newton Raphson - full

lumpm,0 ! Lumped mass off

nsubst,20 ! Number of substeps, 20

neqit,100 ! Max no. of iterations

autots,on ! Auto time search on

lnsrch,on ! Line search on

outres,all,all	! Output data for all substeps
kbc,0	! Load applied 0=linearly interpolated (ramped),
1=stepped	
FK,5,HEAT,3.99e12	
/gst,off	! Turn off graphical convergence monitor
solve	
finish	
/post1	! Enter postprocessor
set,last	! Read in last subset of data
etable,melty,temp,	! Create an element table
esel,s,etab,melty,1922	! Select all elements from table above 1922K
cm,melted,elements	! Name these elements as melted
finish	
!/solu	! Re-enter solution phase
!antype,,rest	! Restart analysis
!ekill,all	! Kill all selected elements
!esel,all	! Re-select all elements
!finish	
/post1	! Re-enter postprocessor
set,last	! Read in last subset of data
esel,s,live	! Select all live elements
plnsol,temp	! Plot the temp contour of the live elements

```

/dev,font,1,courier,bold,o,14,,,,,
/CVAL,1,0,300,600,1200,2400,4800,9600,19200
/REPLOT
finish

/SOLU

antype,4

PHYSICS,READ,Struct

time,100e-9                ! Time at end of analysis

!TRNOPT,FULL

!NROPT,AUTO, ,

!EQSLV,

SOLCONTROL,ON

nropt,full                ! Newton Raphson - full

nsubst,200                ! Number of substeps, 200

DA,5,UX,0

DA,3,UY,0

DA,6,UX,0

DA,4,UY,0

DA,1,UZ,0

autots,on                ! Auto time search on

LDREAD,TEMP,, , , 'point100','rth',' '

/gst,off                ! Turn off graphical convergence monitor

TREF,293,
```


solve

ekill,melted

esel,s, live

finish

/post1

set,last ! Read in last subset of data

PLDISP,0

finish

!PATH OPERATIONS

/post1

PATH,xline,2,1000,20,

PPATH,1,0,0,0,0,0,

PPATH,2,0,50,0,0,0,

AVPRIN,0,0,

!*

PDEF,xlinevon,S,EQV,AVG

/PBC,PATH, ,0

!*

PLPATH,XLINEVON

PATH,zline,2,1000,20,

PPATH,1,0,0,0,0,0,

PPATH,2,0,0,0,-20, 0,

AVPRIN,0,0,

!*
.

PDEF,zlinevon,S,EQV,AVG

/PBC,PATH, ,0

!*
.

PLPATH,ZLINEVON

Appendix H

ANSYS FEM simulation code for Gaussian thermal load

The ANSYS input code used for the modelling and simulation of the micro EDM using a Gaussian thermal load is given below:

```
/filename,gauss100

/title, gauss100

/prep7

ET,1,SOLID90

blc4,0,0,50,50,-20

SMRTSIZE,3                !1=dense;5=coarse

MSHAPE,1,3D                !0=quad/hex;1=tri.teragonal

MSHKEY,0                   !0=free;1=mapped meshing

VMESH,1

KREFINE,5, , ,2,1,1,1      !level 3 depth 1

KREFINE,5, , ,3,2,1,1      !level 2 depth 2

!KREFINE,5, , ,5,1,1,1

/VIEW, 1, -1, -1, 1

/ANG, 1, 60

/REPLO

MPTEMP,,,,,,,,

MPTEMP,1,0
```

MPDATA,DENS,1,,4428.78e-18

MPTEMP,,,,,,,,

MPTEMP,1,293,366,478,688,798,813

MPTEMP,7,923

MPDATA,KXX,1,,6.6e6,7.3e6,9.1e6,10.6e6,12.6e6,14.6e6

MPDATA,KXX,1,,17.5e6

MPTEMP,,,,,,,,

MPTEMP,1,293,478,698,923,1143

MPDATA,C,1,,580e12,610e12,670e12,760e12,930e12

MPTEMP,,,,,,,,

MPTEMP,1,273,473,673,873

MPDATA,ALPX,1,,8.6e-6,9.5e-6,9.7e-6,10.6e-6

MPTEMP,,,,,,,,

MPTEMP,1,77 ,273,473,673,873,1073

MPDATA,EX,1,,114.9e3,105e3,94.7e3,84.1e3,74.2e3,62.8e3

MPDATA,PRXY,1,,.23,.23,.23,.23,.24,.24

PHYSICS,WRITE,Thermal, , ,

PHYSICS,CLEAR

ETCHG,TTS

MPTEMP,,,,,,,,

MPTEMP,1,273,473,673,873

MPDATA,ALPX,1,,8.6e-6,9.5e-6,9.7e-6,10.6e-6

MPTEMP,,,,,,,,

MPTEMP,1,77 ,273,473,673,873,1073

MPDATA,EX,1,,114.9e3,105e3,94.7e3,84.1e3,74.2e3,62.8e3

MPDATA,PRXY,1,,.23,.23,.23,.23,.24,.24

MPTEMP,,,,,,,,

MPTEMP,1,0

MPDATA,DENS,1,,4428.78e-18

PHYSICS,WRITE,Struct, , ,

FINISH

/SOL ! Enter solution phase

PHYSICS,READ,Thermal

TUNIF,293 !INITIAL CONDITION

SFA,3,,HFLUX,0 !BOUNDARY CONDITIONS

SFA,5,,HFLUX,0

SFA,1,,CONV,10000,293 !This is top surface

SFA,3,,HFLUX,0

SFA,4,,HFLUX,0

SFA,6,,HFLUX,0

antype,4 ! Transient analysis

!TRNOPT,FULL

!NROPT,AUTO, ,

!EQSLV,

SOLCONTROL,ON

time,100e-9 ! Time at end of analysis

nropt,full ! Newton Raphson - full

lumpm,0 ! Lumped mass off

nsubst,200	! Number of substeps, 20
neqit,1000	! Max no. of iterations
autots,on	! Auto time search on
lnsrch,on	! Line search on
outres,all,all	! Output data for all substeps
kbc,0	! Load applied 0=linearly interpolated (ramped) ,
1=stepped	
SFA,2,,HFLUX,%gauss100%,293	
/gst,off	! Turn off graphical convergence monitor
solve	
finish	
/post1	! Enter postprocessor
set,last	! Read in last subset of data
etable,melty,temp,	! Create an element table
esel,s,etab,melty,1922	! Select all elements from table above 1922K
cm,melted,elements	!Name these elements as melted
finish	
!/solu	! Re-enter solution phase
!antype,,rest	! Restart analysis
!ekill,all	! Kill all selected elements
!esel,all	! Re-select all elements
!finish	

```
/post1                ! Re-enter postprocessor

set,last              ! Read in last subset of data

esel,s,live           ! Select all live elements

plnsol,temp           ! Plot the temp contour of the live elements

!/dev,font,1,courier,bold,o,14,,,,

!/CVAL,1,0,300,600,1200,2400,4800,9600,19200

!/REPLOT

finish

/SOLU

antype,4

PHYSICS,READ,Struct

time,100e-9           ! Time at end of analysis

!TRNOPT,FULL

!NROPT,AUTO, ,

!EQSLV,

SOLCONTROL,ON

nropt,full            ! Newton Raphson - full

nsubst,200            ! Number of substeps, 200

DA,5,UX,0

DA,3,UY,0

DA,6,UX,0

DA,4,UY,0
```

DA,1,UZ,0

autots,on ! Auto time search on

LDREAD,TEMP,, , 'gauss100','rth',' '

/gst,off ! Turn off graphical convergence monitor

TREF,293,

solve

ekill,melted

esel,s,live

finish

/post1

set,last ! Read in last subset of data

PLDISP,0

finish

!PATH OPERATIONS

/post1

PATH,xline,2,1000,20,

PPATH,1,0,0,0,0,0,

PPATH,2,0,50,0,0,0,

AVPRIN,0,0,

!*

PDEF,xlinevon,S,EQV,AVG

/PBC,PATH, ,0

!*

PLPATH,XLINEVON

PATH,zline,2,1000,20,

PPATH,1,0,0,0,0,0,

PPATH,2,0,0,0,-20, 0,

AVPRIN,0,0,

!*
.

PDEF,zlinevon,S,EQV,AVG

/PBC,PATH, ,0

!*
.

PLPATH,ZLINEVON

Appendix I

List of related publications

The publications and presentations made during the period of this research are listed below:

International refereed journals:

1. **Murali, M.** and Yeo, S.H. (2005) Process Simulation and Residual Stress Estimation of Micro-Electrodischarge Machining Using Finite Element Method, Japanese Journal of Applied Physics, 44 (7A), 5254-5263
2. Yeo, S.H., **Murali, M.** and Cheah, H.T. (2004) Magnetic field assisted micro electro-discharge machining, Journal of Micromechanics and Microengineering, 14 (11), 1526-1529
3. **Murali, M.** and Yeo, S.H. (2004) A Novel Micro Erosion Technique for the Fabrication of High Aspect Ratio Micro-grooves. Microsystem Technologies, 10 (8-9), 628–632
4. **Murali, M.** and Yeo, S.H. (2004) Rapid Biocompatible Micro Device Fabrication by Micro Electro-discharge Machining. Biomedical Microdevices, 6 (1), 41-45
5. Yeo, S.H. and **Murali, M.** (2003) A new technique using foil electrodes for the electro-discharge machining of micro grooves, Journal of Micromechanics and Microengineering, 13 (1), N1–N5

Conferences / Symposium:

1. **Murali, M.**, Yeo, S.H. and Rajurkar, K.P (2005) A Study of Tool Electrode Materials and Flushing Techniques in micro EDM, Proceedings of the 20th Annual Meeting of American Society for Precision Engineering (ASPE) held on October 9-14, 2005 at Norfolk, Virginia, USA, 492-495.
2. Yeo, S.H., **Murali, M.** and Balakrishnan, S (2005) Effect of tool electrode material on the spark erosion of micro grooves, Proceedings of the First Manufacturing Engineering Society International Conference (MESIC-SIF) held on September 19-21, 2005 at Calatayud, Spain
3. **Murali, M.** and Yeo, S.H (2004) Nano-characterization of spark eroded surfaces, Poster presented in the Japan – Singapore symposium on Nanoscience and Nanotechnology held on 2-3 November 2004 in National University of Singapore, Singapore