DESIGN, DEVELOPMENT AND STUDY OF OPTIMAL PARAMETERS OF A MICRO WIRE ELECTRICAL DISCHARGE MACHINING (μWEDM) DEVICE

SADIQ MOHAMMAD ALAM

NATIONAL UNIVERSITY OF SINGAPORE

2006

DESIGN, DEVELOPMENT AND STUDY OF OPTIMAL PARAMETERS OF A MICRO WIRE ELECTRICAL DISCHARGE MACHINING (μWEDM) DEVICE

Sadiq Mohammad Alam

B. Sc. in Mechanical Engineering,

Bangladesh University of Engineering and Technology (BUET)

A THESIS SUBMITTED

FOR THE DEGREE OF MASTER OF ENGINEERING

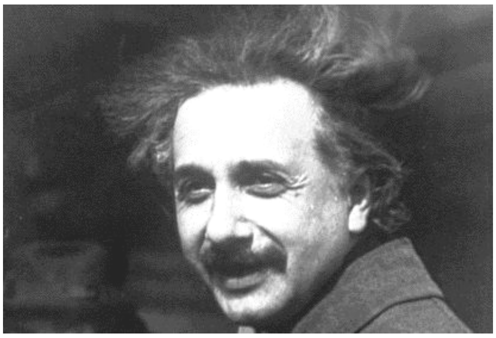
DEPARTMENT OF MECHANICAL ENGINEERING

NATIONAL UNIVERSITY OF SINGAPORE

2006

If we knew what it was we were doing, it would not be called research, would it?

- Albert Einstein



ACKNOWLEDGMENTS

•

The true acknowledgement belongs to the Divine

•

I would like to express my deepest and heartfelt thankfulness and appreciation to my supervisor, Professor Mustafizur Rahman as well as to my former supervisor Dr. Lim Han Seok, for their invaluable guidance, continuous support and encouragement throughout the research work. Their comments and advice during the research has contributed immensely towards the success of this work. In addition, their patient guidance and suggestions has also helped me in learning more.

I also would like to thank National University of Singapore (NUS) for supporting my research by the research scholarship and to Advanced Manufacturing Lab (AML) and Micro Fabrication Lab for the state of the art facilities and support without which the present work would not be possible. Special thanks must go to Associate Professor Wong Yoke-San for his valuable guidance and advice time to time.

I would also like to thank the following staff for their sincere help, guidance and advice: Mr. Lee Chiang Soon and his staff from workshop 2, Mr. Tan Choon Huat and his staff. I also acknowledge helpful co-operation from NUS Spin-off company MiktroTool Pvt Limited's staff Mr. Asad, Mr. Pallani and Mr. Chung Mun.

I would also like to offer my appreciation for the support and encouragement from my research colleagues and lab mates who have encouraged and helped me along the way. My appreciation goes to Sharon Gan, Altabul Quddus, Wang Zhigang, Masheed Ahmad, Sazedur Rahman, Majharul Islam, Tabassum, Indraneel Biswas, Woon Keng and many more. I was lucky to work with FYP Student Kevin Wong who has helped greatly and co-operated in conducting experiments, sharing research ideas and moving forward the research.

Last but not least my heartfelt thank to my parents who have always been there to support me and send their best wishes wherever I am.

Table of Contents

SUMMARY

Wire electro discharge machining (WEDM) is a specialized thermal machining process, capable of accurately machining parts with varying hardness or complex shape. It is now a widely accepted non-traditional material removal process which makes use of electrical energy to transform into thermal energy. Micro WEDM (μWEDM) is gaining popularity because of its low set-up cost, high accuracy, large design freedom and ability to precision engineer in micro-dimensions. The process is capable of producing small parts with good surface finish and allows parts to be manufactured relatively easily, since it impart minimal stress to the work piece during the machining process.

In this research a fully functional μWEDM device was designed and developed beginning from the early concept stage. The WEDM device was designed as an interchangeable part of the already developed multi-process capable CNC machine to enable wire cut EDM operation. Wire tension and speed control was also incorporated in the device.

Pertinent parameters play a very vital role in WEDM and because of this the effect of different parameters on the machining characteristics needs to be studied carefully. The optimum selection of manufacturing conditions is very important in manufacturing processes as these determine surface quality and dimensional precision of the machined parts. Thus, it is necessary to know, in advance, properties relating to surface quality and dimensional precision by means of experimental investigation by taking into account machining characteristics such as gap width, surface roughness,

material removal rate, etc. Owing to the complexity concerning the sparking phenomena and the complicated stochastic nature of the process, the detection of optimal cutting parameters is still a great challenge. The selection of cutting parameters for obtaining higher cutting efficiency or accuracy in WEDM is still not fully solved, even with the most up-to-dated CNC WEDM machine, specially when it comes to μWEDM.

In this work different major machining parameters were identified and elaborated experiments were performed. Part of this research was focused on aspects related to surface quality and dimensional precision, which are one of the most important parameters from the point of view of selecting the optimum conditions of processes.

The identification of optimal parameter and the machining trends were one of the prime objectives in the current work. After the detection and elaborate understanding of the interaction among parameters, different kind of machining job was performed. Primarily slots of different length were cut. Also different micro shapes and parts were fabricated by WEDM. The gap width of the slots, surface profile and roughness, machining time, material removal rate were observed.

The experimental results were interpreted from higher magnification microscopic images and SEM observations. The gap widths were calculated, surface profile was drawn and surface roughness was calculated. Through a series of rigorous experiments, a set of optimum parameters have been achieved. Sample micro parts were also manufactured using these parameters, and MRR and gap width was noted. The main

parameters affecting the characteristics were found to be voltage, current or energy, spark on time and wire tension.

A summarized table for optimum parameter was also developed to facilitate the usage of the μWEDM device to achieve desired machining characteristics. Optimal parameter value range for voltage, resistance, spark on/off time, wire tension and speed, EDM speed are compiled. Based on the experimental results and comparison with previous research works it was found that the developed μWEDM device is capable of obtaining reasonable machining characteristics. Few recommendations for further improvements of the device are also put forward.

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

1.1 MOTIVATION

1.1.1 Machine Development

The development in the area of MEMS and other micro mechanical components, the growing needs for micro-feature generation and applications of advanced, difficult-to-machine materials have made the micro-wire EDM an important manufacturing process to meet these demands. Fabrication trend is continuously driving towards miniaturization. In present day the fields of MEMS, biomedical engineering and microsurgery, communication technology all demand micro-parts with high precision and accuracy. The drive for miniaturization will provide micro-systems that promise to enhance health care, quality of life and economic growth in such applications as micro-channels for lab-on-chips, shape memory alloy parts, fluidic graphite channels for fuel cell applications, sub miniature actuators and sensors, and medical devices [Corbett et. al, 2000; Madou, 1997; Weck et. al., 1997 and Lang, 1999]. Micro-EDM is considered as one of the most promising methods in terms of size and precision. It has advantage over other fabrication processes, such as LIGA (a photo-lithography method), laser, ultrasonic, ion beam etc., because of its economical advantage. Micro-machining techniques such as micro WEDM do not require very expensive setup such as required in lithographic methods. The cutting force is comparatively low, which makes the WEDM an important process to manufacture precise, intricate, and miniature features on mechanical components. Also the majority of other unconventional processes are slow and limited in planar geometries.

The diverse application requires fabrication of such micro parts on exotic, newly developed materials which are often difficult to machine with conventional machining processes. Often these unconventional materials have very different characteristics, which require special machining strategy such as laser beam machining, ultrasonic machining, electro-discharge grinding (EDG) or electro-discharge machining (EDM) etc.

Although these unconventional machining processes have been successfully applied in many areas, the gap between conventional and unconventional machining processes are getting more and more narrow. As the unconventional machining processes are becoming more and more commonplace, they are no longer isolated from already recognized prevalent processes such as turning, milling and drilling. Thus the incorporation of both conventional and unconventional machining processes on a single machine unit will really open up better potential. It allows to work on intricate, challenging shapes and at the same time that requires both conventional and unconventional machining at the same time. Multi-process micro machining is becoming the trend of future fabrication technology. There is greater demand both from the industry and research community to incorporate both conventional and non-conventional micro-machining technologies in a single machine.

In order to address this issue an attempt was undertaken to develop a multi-process capable machine at National University of Singapore (NUS). The objective set was such that the machine will be able to perform non-conventional machining such as micro Wire Electro Discharge Machining (WEDM), Wire Electro Discharge Grinding (WEDG), Electro Chemical Machining (ECM) and conventional machining operations such as Turning, Milling and Drilling.

There are a number of commercial EDM and Wire EDM machines manufactured by different companies, but in research arena independent efforts to develop micro EDM and WEM machine are limited in number. In order to study the characteristics of micro EDM phenomena, development of such machine is the most important first step. It is thus, of considerable interest and importance to design and develop a Micro EDM machine capable of multi-process operations and to study closely.

1.1.2 Parameter Study

In WEDM the machining characteristics are mostly influenced by the parameters chosen. In WEDM the principal action that is responsible for material removal is sparking. The EDM process is based on the thermo-electric energy created between a workpiece and an electrode submerged in a dielectric fluid. The sparking process being stochastic in nature is not definite and does not have a predictable nature. Even after such a long time following the development of EDM technology, there is no concrete explanation regarding the discharge process and how it affects the EDM operation.

Thus identifying the major parameters in the first place and then understanding the behavior of individual parameters and also their interacting effect on the machining characteristics is important. Selection of proper cutting parameters is required to obtain higher cutting efficiency and accuracy in WEDM.

The information to select proper WEDM process parameters for newly developed materials or micro features is not readily available, specially when it comes to a newly developed machine. Manufacturers of EDM machines usually provide a database of suggested process parameters for commonly used work and electrode materials under typical operating conditions. Such database cannot meet the growing new EDM applications by new generations of machines and also for machining of miniature features. Optimum utilization of the capability of the WEDM process requires the selection of an appropriate set of machining parameters. The second part of this research concentrates to seek the optimum parameters for μWEDM.

1.2 SCOPE OF THE STUDY AND OBJECTIVES

The scope of this study can be briefly summarized as follow:

- In this study a primary objective is to design and develop a fully functional μWEDM device. The WEDM device will be designed as an interchangeable part for the already developed multi-process capable CNC machine tool to perform WEDM operation.
- The device will be calibrated and tested for its performance. The interactions of different machining parameters are to be investigated and elaborate experiments will be performed to understand their role on the machining characteristics.
- Among the machining characteristics, sub-objectives will be to reduce the gap width as low as possible, to achieve good surface roughness and also to check

for faster machining rate. The machining effects were evaluated and compared in terms of -

- Gap width
- Machining time, and
- Surface roughness

- The experimental results will be interpreted and the machining effects due to the pertinent parameters are to be explained.
- Opportunity for improvement or further development of the device will also be sought.

1.3 METHODOLOGY

There are two possible approaches for determining the relations between the prime WEDM parameters and the major machining characteristics. The first approach involves the development of an appropriate model of the process that correlates with the major parameters. Thus the model can be used as an estimate for the electro-discharge machining phenomena. But with WEDM being a stochastic process, such models to completely account for the vaporization, ejection and resolidification are not available. Various thermal models proposed for EDM [Pandit and Rajurkar, 1983; Spur and Schonbeck, 1993; Snoyes and Dijck, 1997, Jennes and Snoeys, 1984] had shown that the complexities due to the stochastic nature of the multiple discharges render difficulties in analyzing the process theoretically [Liao, Y. S and Y. P. Yu, 2004].

Also modeling effort taken previously can not be directly applied to a newly developed machine where the conditions are different. Because of differences in controller and behavior of discharge circuit of each machine has its own characteristics. Even if the prime mechanisms are same, because of the power circuits and controllers two machines can have unpredictable and very different results from the parameters. The effect of the parameters on machining for this newly developed machine can not be generalized accurately from earlier parameter studies done on other machines. This gives rise to the need of the current work.

The second approach in determining the relations between the prime WEDM parameters and the major machining characteristics is experimental. It is the direct approach of measuring gap width (kerf), material removal rate and surface roughness by varying the major parameters such as open gap voltage, pulse on time etc. The method depends on actual data gathered from the experiments and analyzing the results. This demand for the availability of expensive equipment and facilities, but have more relevance since the experiments are conducted in real environment on the exact machine under investigation. The experimental data later can be compiled in a database to help the machinist for future parameter settings. For the current research the second approach has been chosen.

1.4 ORGANIZATION OF THE DISSERTATION

There are ten chapters in this dissertation. In this chapter the background about the motivation for WEDM machine development is discussed. Also the need and method of parameter study is highlighted briefly. The scope and research objectives are also summarized.

Chapter 2 is divided into six sub-sections giving a comprehensive review of the literature. The overview of the WEDM process is discussed in details. Also previous work on WEDM machine development is presented. Parameter study and machining characteristics are also reported.

Chapter 3 describes the design and development of the WEDM device. The factors considered in the design of the device are discussed. Also the modification made along the way and algorithm for the controller are also incorporated.

Chapter 4 presents the experimental details such as experimental setup, workpiece, machining parameters and apparatus used for measurement.

Chapter 5 details the experimental analysis. The effects of major parameters such as voltage, current, spark on time, wire tension, wire speed, EDM speed are presented in graphical format in terms of machining time, gap width, material removal rate and surface roughness. The trend of the parameters and their underlying behaviors are also analyzed to understand the interaction of them and effects on machining characteristics.

Chapter 6 contains the critical study of the WEDMed surfaces to understand the post-process surface integrity that includes the nature of the debris, heat affected zone and other surface features.

Chapter 7 presents WEDMed micro-parts and shapes that were cut to demonstrate the ability of the WEDM machine and the application of the investigated optimal parameters. The manufactured WEDM shapes / parts include micro-channels, square shaped micro gear, clock dial, curved path and complex shaped logo.

In Chapter 8, the study of wave forms from oscilloscope signal is presented. Also a comparison has been made between RC circuit and transistor pulse circuit. The macro scenario obtained from the oscilloscope signal gives an overall picture of the conditions of the process in real time.

Chapter 9 puts forward the results of the optimum parameter study. The results are compiled and the best range of values for obtaining faster material removal rate, minimum gap width and minimum surface roughness are derived. Also in this chapter the problems encountered during the research work are mentioned for successive study.

Chapter 10 concludes the thesis with a summary of contributions and recommendations for further development.

Chapter 2

LITERATURE REVIEW

2.1 INTRODUCTION

Wire electrical discharge machining (WEDM) is one of the variants of EDM technology that can be very well adapted for the micro-fabrication applications. The advance of semiconductor, telecommunication and biotech industries in recent years has called for the fabrication of miniature products with new and improved functions. From application point of view, micro parts, such as the dies for making an IC lead frame, find use in semiconductor industry and medical devices and microelectronic medical implants in the biotech industry, which are all examples of the increasing demand for products with larger aspect ratio and higher spatial resolution.

This chapter introduces an overview of the WEDM process and then focuses on the WEDM machine development and finally the parameter study aspect.

2.2 HISTORICAL BACKGROUND OF EDM AND WEDM

The very phenomenon of removal of metal by electrical spark was first noticed around the year 1700 by Benjamin Franklin. But the application of the principle took almost two hundred and fifty years. In 1948 the Lazarenkos, a Russian husband and wife first applied it to a machine for stock removal. They adapted the first servo-system to an EDM machine, which offered some apparent degree of control that is required. Initially EDM was used primarily to remove broken taps and drills from expensive parts. These were quite crude in construction with hand-fed electrodes.

WEDM was first introduced to the manufacturing industry in the late 1960s [Ho et. al., 2004]. The WEDM technology over conventional EDM technology was the result of an effort to replace the machined electrode which was often difficult to produce. The major evolution of the machining process followed only when in the late 1970s computer numerical control (CNC) system was incorporated into WEDM.

2.3 OVERVIEW OF THE WEDM PROCESS

2.3.1 Principles of WEDM

WEDM is a widely accepted non-tradition material removal process. The material removal mechanism of WEDM is the same as that of electrical discharge machining. It has been widely accepted that the metal removal mechanism in EDM is predominantly a thermal effect in nature [Ho et. al., 2004].

The basic principle behind EDM process is a series of electric sparks between the workpiece and wire electrode. The electrical discharging process generates a tremendous amount of heat causing melting or even evaporation in the local surface layers on both wire-electrode and workpiece sides. The heat also causes vaporization of the dielectric fluid and induces high-pressure waves, which wash out the molten and/or vaporized metal into pieces from the workpiece. Continuously injected dielectric fluid then carries the droplets of metal away. WEDM is considered as a unique adaptation of the conventional EDM process. However, WEDM utilizes a continuously traveling wire electrode made of thin copper, brass or tungsten material, which is capable of achieving very small corner radii. It is desirable that the wire electrode and workpiece both be electrically conductive.

2.3.2 Characteristics of the Process

- WEDM is a specialized thermal machining process.
- In terms of working principle, method of material removal etc. WEDM is very similar to die sinking or conventional electro-discharge machining.
- It makes use of electrical energy that generates a channel of plasma between the cathode and anode and turns it into thermal energy.
- The temperature involved is in the range of 8,000 to 12,000 °C or even as high as 20,000 °C initializing a substantial amount of heating and melting of material on the surface of each pole.
- Utilizes a traveling wire that advance very close to the desired machining surface.
- Removes material by rapid, controlled, repetitive spark discharges.
- Uses dielectric fluid, generally deionized water for WEDM to flush removed particles, control discharge, and cool wire and workpiece
- Performed on electrically conductive workpieces, but semiconductive or less conductive material can also be used as workpiece with special arrangement
- Can produce complex multi-dimensional shapes.
- Relatively fast process.

2.3.3 Understanding the sparking phenomena in EDM and WEDM

In his paper Shumacher [2004] rightly chose his paper's title, which summarizes the current understading of sparking phenomena in Electro discharge machining. The title of his paper was 'After 60 years of EDM the discharge process remains still disputed.' In 1943 Lazarenko proposed the basic mechanism of EDM and since then the very nature of spark is yet not properly understood among scientific community. There are differences in opinion regarding the spark ignition theories as well as in respect to metal removal procedure, such as thermal effects, thermal shocks, mechanical stress etc.

To understand the sparking phenomena, its worth following the development sequence of the sparks in electrical discharge.

1. When the gap voltage is applied, an electric field or energy column is created. This field gains highest strength once the electrode and surface are closest, in this case the wire electrode and workpiece.
2. Generally the insulating liquid or dielectric fluid provides insulation against premature discharging.
3. The electrical field eventually breaks down the insulating properties of the dielectric fluid.
4. Once the resistivity of the fluid is lowest, a single spark is able to flow through the ionized flux tube and strike the workpiece.
5. The voltage drops as the current is produced and the spark vaporizes anything in contract, including the dielectric fluid, encasing the spark in a sheath of gasses composed of hydrogen, carbon and various oxides. The area struck by the spark will be vaporized and melted, resulted in a single crater.
6. Due to the heat of spark and because of produced contaminates from workpiece, the alignment of the ionized particles in the dielectric fluid is disrupted and thus the resistivity increase rapidly.
7. Voltage rises as resistivity increases and the current drop as dielectric can no longer sustain a stable spark. At this point the current must be switched off, which is done by $T_{off.}$

8. During the current off time, as heat source is eliminated the sheath of vapor that was around the spark implodes. Its collapse creates a void or vaccum and draws in fresh dielectric fluid to flush away debris and cool the area. Also the reionization happens which provides favorable condition for the next spark.
9. Together with on and off time a single cycle of electrical discharge machining occurs.
10. The whole process repeats itself successively for continuous electric discharge machining.

2.3.4 Distinction between Spark and Arcing

The physicists are having difficulty to clearly define differences between sparks and arcs. Generally sparks refer to so called *desired condition* which produce manageable, precise and good quality surface. On the other hand, 'Arcing' characterizes deteriorated machining, which results in discharge concentration, melting and overheating at surface spots. It is the arcing condition, which is also sometime referred to short circuit.

2.3.5 External forces and vibration

In WEDM device arrangement, wire electrode is supported by two guides and is moving down the guide at a uniform velocity. During the electro discharge process, there are several forces that are effective.

External forces involved in the process are:

1. An axial tension on the wire

2. An electro-static force produced by the electric field between the workpiece and the wire electrode
3. An electro-dynamic and explosion force caused by spark discharge and
4. The damping force caused by the dielectric medium

Guo et. al. observed that the electro-static force is uniform along the wire and has a lesser effect on wire fluctuation [Z. N. Guo et. al. 2003].

2.3.6 Setup and Equipment

WEDM is a variation of the conventional die sinking EDM. Initially, this type of equipment was used as a slicing machine for thin-walled structure. With the help of computer numerical control, complex shapes can be cut without using special electrodes. The narrow kerf and dimensional accuracy of the process make it possible to provide close-fitting parts.

A typical wire EDM setup consists of:

- Controller circuit
- The main Wire EDM attachment
- Workpiece holder and base
- Mechanism for the flow of dielectric fluid.

2.3.7 Typical Tools and Geometry Produced

Generally in WEDM a traveling copper, brass, tungsten or molybdenum wire from 30 micron to 100 micron in diameter is used for the electrode. Tension in the wire and controlled positioning produce a very narrow kerf. This arrangement permits the cutting of intricate openings and tight radius contours, both internally and externally, without a shaped tool. Because the wire is inexpensive and for the sake of geometric accuracy, it is generally used once.

2.3.8 Tool Style

Electrode wire is available in many materials such copper, steel, brass, tungsten, molybdenum etc. Also now a days in-order to combine different properties of materials, coated wires as well as alloys are also used. The wire comes in several diameters to suit a variety of needs.

Mechanical and chemical properties that are well sought of in choosing wire materials are:

- Tensile strength
- Fracture resistance
- Conductivity
- Vaporization point
- Hardness.

Brass, copper and tungsten are the most common electrode wires for cutting holes and slots in nearly all metals. Copper-tungsten alloys, steel and molybdenum alloys are also used for cutting a variety of materials, especially non-ferrous metals.

Table 2.1: Wire Electrode as tool in WEDM

Application based on electrode wire diameter	
Wire Diameter (μm)	*Application*
25 - 50	Intricate openings
70 - 100	Tight radius, slots and holes
100 – 300	Internal and external features
Application based on electrode material	

Wire Material	*Application*
Brass	All metals, holes
Copper	All metals, holes
Tungsten	All metals (specially refractory metals), small slots or holes
Copper-Tungsten	All metals, carbide slots, thin slots
Steel	Nonferrous, holes
Molybdenum	Refractory, holes

2.3.9 Advantage of WEDM over die sinking EDM

WEDM has a number of advantages over die sinking such as:

- More flexibility in terms of the shapes and surface to be generated
- Faster machining is possible
- Concern for electrode wear is eliminated
- No need to fabricate complex shape electrodes prior to actual machining.
- The shape to be generated can be controlled precisely using computer numerical control.

2.3.10 Application of WEDM for micro-fabrication

Already there has been some research work demonstrating the feasibility of micro-fabrication using WEDM technology. Luo et. al. [1992] have investigated the machining performance of WEDM in the wafering of silicon. They suggested that EDM cutting can be profitably applied as an alternative for some wafering tasks which are performed by other methods such as inner diameter slicing or sawing. The conventional inner diameter slicing equipment has its limitations because of its mechanically abrasive nature.

The ability to machine low electrical conductive material can have very promising implications on micro-fabrication. Previous research have shown that EDM can be successfully applied to machine ceramics, including single phases and composites of ceramic-ceramic and ceramic-metal, if the electrical resistivity is below 100 Ωcm [Faulk, 1993; Konig and Panten, 1993].

Apart from machining on conductive materials, EDM of non-conductive materials workpiece is also possible with an assisting electrode [Fukuzawa, 1995 and Mohri, 1996]. The use for semiconductor wafer was something very foreign to it until it was first reported by Masaki et. al [1990]. They reported that machining speed of silicon is almost double of that of stainless steel. Importantly it was found that the wear of the wire is very low for silicon.

Staufert et. al. [1993] fabricated a silicon spring/frame combination out of a silicon wafer. Silicon wafer used was n-type (001) oriented, thickness of the element was 0.3 to 0.5 mm. Experimental investigation on the performance of the spring showed very promising result. They exposed the spring to over three-millions working cycles and found no detectable fatigue. Also the spring showed very good linearity. To restore the crystalline structure of the silicon wafer, a thermal annealing step and an isotropic etching process was done. The electrode used was copper wire.

Luo et . al. [1992] succeeded in slicing silicon wafers of 94 to 210 micron thickness using an n-type silicon ingot. The resistivity was 7 to 15 ohm and the cutting speed obtained was 170 mm^2/min. To reduce high contact resistance the ingot was nickel-plated. The surface roughness, cutting efficiency and micro-structures under different energy intensities are observed. But the effects of this procedure are not overall well demonstrated. Peng and Liao [2003] studied WEDM strategy for slicing silicon ingots.

They measured machining rate and surface roughness under various currents on time and servo voltages in both water immersed and water flushing WEDM machines. Stable machining rate of about $76mm^2$/min and R_a value of 3.6 micron is reported.

Liao et. al. [2005] fabricated high aspect ratio microstructure arrays. They implemented some unique techniques for controlling the vibration, removing debris, application of proper tension etc. A microstructure with a volume of 1 mm^3 and an aspect ratio of 33 was successfully fabricated. Dimensional and geometric accuracy was no greater than 0.6 μm and 1 μm respectively and a surface roughness of R_{max} = 0.44 μm was achieved. In another paper Liao et. al. [2005b] have demonstrated successful micro-fabrication of micro outer and internal gear, micro rack, miniature pagoda with intricate curves etc. Weng et. al. [2003] have employed WEDM to fabricate micro-electrodes up to 20 μm. In this case copper rod was the work-piece and wire electrode was brass.

Uhlmann et. al. [20] have conducted research on micro-machining of cylindrical parts by EDG. Techniques like electric discharge turning (EDT), electrical discharge grinding (EDG) and wire electrical grinding (WEDG) were used and compared with respect to the influence by the machining effects developing at high peripheral speeds. EDM is considered to fabricate micro-electrodes and micro-parts as well [Weng et. al, 2003]. The state of the art of different aspects in WEDM is well established in scientific articles and journal publications. The contribution of the present paper is to focus the challenges of WEDM in micro-fabrication.

2.4 MACHINE DEVELOPMENT

Literature review reveals that machine development on μWEDM has not received much attention in recent years, all though there are a lot of commercial EDM and Wire EDM machines manufactured by different companies. Several EDM machine tools builders such as Agie Charmilles Ltd of Switzerland, Fanuc Ltd. and Sodick Inc. of Japan have developed commercial WEDM machine.

(a) (b)

Figure 2.1: Example of two commercial WEDM machine used in the industry
(a) ROBOFIL 6050TW, a wire cut EDM machine by Charmilles, www.charmilles.com
(b) FANUC ROBOCUT α-0iC,

Mu-Tian et. al. [2004] have developed a prototype μWEDM machine using open architecture CNC system and wire transport system. Tungsten wire of diameter 50 micron and 70 micron brass wire is used. In order to control the tension of the wire, the transport system comprises of wire reel, electromagnetic brake, idle roller and DC motor. It is acknowledged in the paper that due to various machining conditions and the dynamic nature of the torque – it is difficult for a classical control strategy and modern control technology based on a well-defined mathematical model to control the wire transport system of WEDM. Thus, they have used fuzzy control strategy for control purpose under the variations of the system parameters.

The wire transport system utilized for tension control purpose in their paper is quite complex compared to what has been implemented in the current work. A much easy to use approach has been used in the WEDM device which has the added advantage of less complex nature and easy to manipulate.

The power supply system used in their machine is composed of a low energy discharge circuit and an iso-frequency pulse generator. Pulse states have been classified as open circuit, normal discharge and abnormal discharge by means of the level of gap voltage and discharge current. But the power supply has the drawback of excessive energy storage into the inductive part. If this excessive energy remains in the discharging circuit and not drained out, there is a possibility of instability to the discharging and also could cause damage to the internal circuit of the power supply system. In their experimental analysis, they found out that the capacitance of energy is the most important factor that affects the peak current.

Yunn-Shiuan et. al. [2005] and also Y. S. Liao et. al. [2005] have developed precision versatile CNC wire-EDM machine. The main features of the machines developed are their ability to cut vertically, horizontally or even diagonally. Similar to the present research, the modularized design of the system the machine can perform μEDM, micro-high speed milling, μEDM milling etc.

They have used 20 micro-meter brass wires. For tension control purpose they have used magnetic force method. For their system, the wire receiving spool is the driving wheel, and the wire-giving pool is the passive wheel. The wire is led between two disks with small opening in between through which the wire is led. By applying magnetic force the opening is controlled which leads to the control of the wire tension. But one criticism of the system is that below certain values of the tension the thin diameter wire start to show necking phenomena. Also they used a rubber holder in contact with the wire which functions as a vibration absorber. There is also another problem that arises from the magnetic force controlled tension mechanism. The magnetic effect generates hystersis effect which causes unsteady movement in the micro wire. For pulse generation, the resistance-capacitance (RC) circuit is employed as the discharge mechanism.

2.5 PARAMETER STUDY

In Wire EDM there are a number of parameters that influence the machining characteristics. Identifying the major parameters is the first step before proceeding to finding the optimum parameter. Because of the nature of the process, the major parameters for EDM and WEDM are similar. From literature concerning EDM and WEDM the parameters which are identified as the major ones are:

1) On time (pulse on time, t_{on})
2) Off time (pause off time, t_{off})
3) Duty Cycle
4) Voltage
5) Current
6) Wire Tension

From the current WEDM device additional parameters are also under investigation. Such parameters are wire speed, resistance, EDM speed (servo speed), open value and short parameter. Brief descriptions of the major parameters in WEDM are given here:

On-Time: It is one of the most important parameter in EDM or WEDM. This is the duration of time (μs) the current is allowed to flow per cycle. Material removal rate is directly proportional to the amount of energy applied during this on time. This energy is really controlled by the peak current and the length of the on-time. The main EDM operation is effectively done during this on-time. The spark gap is bridged, current is generated and work is being done. With longer period of spark duration, the resulting craters will be broader and deeper; therefore, the surface finish will be rougher. Shorter spark duration helps to obtain fine surface finish.

Off-Time: This is the duration of time between the two successive sparks when the discharge is turned off. Off time is the duration of rest pauses required for reionization of the dielectric. This time also allows the molten material to solidify and to be washed out of the arc gap. If the off-time is too short, it will cause sparks to be unstable, more short circuiting will occur. When pulse off time is shorter, the number of discharges within a given period becomes more. This results in higher machining speed, but surface accuracy becomes poor because of a larger number of discharges.

Although larger off-time will slow down the process, it can provide stability required to successfully EDM a given application. When the off time is insufficient as compared to on time, it will cause erratic cycling and retraction of the advancing servo motors, slowing down the operation. Minimal off-time is a key to maintain optimum machining speed.

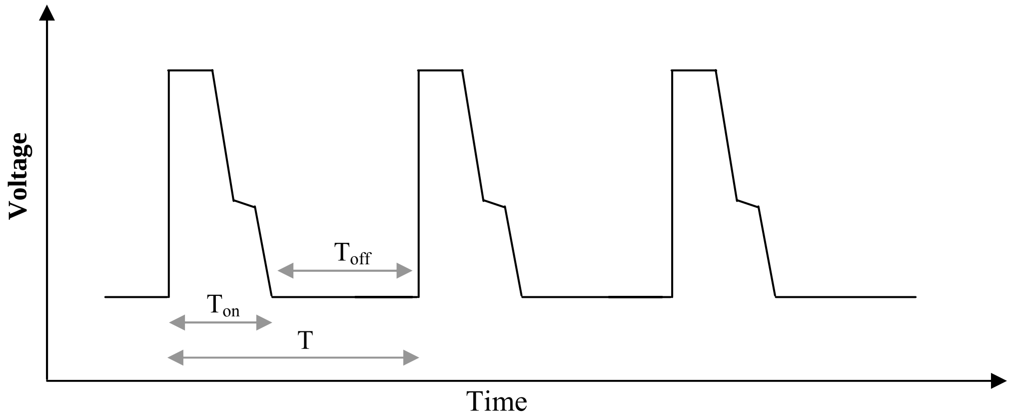


Figure 2.2: Definition of spark cycle, T and spark on time, T_{on} in the EDM sparks cycle: A typical waveform a voltage between the workpiece and wire electrode during EDM. The spark on-time or pulse on-time, T_{on} is the duration when actual sparking occurs. Pulse off-time, T_{off} is when sparking is off. Total cycle, T consist of T_{on} and T_{off}. As seen from the figure that the voltage drop suddenly when the spark occurs.

Duty Cycle: Duty cycle is the relationship of the on-time to the off-time. It is a measure of efficiency and is calculated by dividing the on time by the total cycle time. But often this parameter can give misleading indication. For example different values of on time and off time combination may give the same duty cycle, yet the machining characteristics can be quite different. A T_{on} value of 5 and T_{off} value of 10 will give the same duty cycle of 0.333 such as T_{on} of 10 and T_{off} of 20. But second set of T_{on} and T_{off} will certainly cause more erosion since the pulse on time is double than the first set. As a result of this, duty cycle has not been used as a parameter in the current study.

Voltage: It is the voltage applied between the anode and cathode. The applied voltage determines the total energy of the spark. If the voltage is high, the erosion rates increase and thus higher machining rate is achieved. But at the same time, higher voltage will also contribute to poor surface roughness. In order to achieve higher machining rate, higher voltage may again be the prime reason for wire breakage. For micro wire EDM thus a very moderate value of voltage need to be employed.

Current: This is another very important parameter that determines almost all the major machining characteristics such as machining rate, surface roughness, gap width etc. During machining the current level fluctuates. The term 'peak current' is often used to indicate the highest current during the machining. The higher the peak current setting, the larger is the discharge energy. From experimental evidences of the previous research it seems that sensitivity of the peak current setting on the cutting performance is stronger than that of the pulse on time. When the peak current setting is too high, wire breakage may occur frequently.

Wire Tension: Wire tension is an influential parameter, specially for micro Wire EDM. The amount of wire tension affects the dynamic stability condition of the whole process. The deflection of the wire happens due to different kind of forces working on it, such as electromagnetism, flushing and pressure of the spark [Hewidy, M. S. et. al., 2005]. If tension is less, there is a greater chance of wire bending and also inaccuracy in machining. Because of continuous motion of the wire, if proper tension is not maintained, there could be high vibration at the machining area. This can cause to undesirable gap width, excessive short circuit and even wire breakage. Too high wire tension again can cause the wire to break often.

Wire Speed: It is the velocity of the wire at which it moves across the workpiece during machining. The effect of wire speed has been investigated in this research since it is not given due consideration in the previous research works.

EDM Speed: EDM speed is basically the speed at which the wire is fed during the continuous machining condition. The speed is controlled by the servo motor. The effect of EDM speed is also not studied in details in the previous research work, although it can have significant influence on the machining conditions.

Resistance: In the currently developed machine, there is providence to vary the resistance value. The change of resistance in effect changes the amount of current applied for WEDM. The applied energy is thus a function of the resistance. In the machine 4 different level of resistance are used, 6.8, 15, 33 and 100 ohm.

Short: The parameter 'Short' in the CNC program is a parameter to determine how many continuous sparks will be considered as short circuit. It is primarily a control parameter. The literature investigations show that the published work available do not provide any specific information on the control parameter, short detection and its effect on machining characteristics.

From the basic understanding of the spark phenomena in electro-discharge machining it is conceptuable that short detection parameter has it's implications for the machining result. This is explained below:

- When short parameter is set to high value, there will be more continuous sparks before the discharge circuit is turned off. Thus a large value is helpful to machine faster.
- Because of less successive sparks, a smaller value is helpful for better machining surface, So crater generated will be less intensive, which translates to better surface.

- But too large will mean faster machining but bad machining surface.
- Too smaller means better surface but too long machining time.

Open: It is another control parameter that determines how long the machining be withdrawn once a short circuit or any other unfavorable machining condition occurs. The open parameter consists of the amount of time a complete cycle takes that is the sum of pulse on time and off time. If the value of open is 3 that imply that the time of withdrawal would be 3 times 1 complete cycle (pulse on time + pulse off time). It is a passive parameter like pulse off time, never the less whether the parameter have any significant impact is under investigation.

2.6 MACHINING CHARACTERISTICS

Along with the parameters, major performance measures or machining characteristics that are generally studied in the literature are:

1. Kerf or Gap width
2. Material removal rate or cutting speed
3. Surface roughness

In WEDM the problem of wire breakage is a major one. Hence focus has been given on this issue as well. The phenomena relating to WEDM parameters are complex and mostly stochastic in nature. Thus it puts forward challenges in the understanding of the effects and interaction of the parameters. From the design, development and control up to the actual machining, there are numerous challenges in micro WEDM. In order to get desired micro-machining result all the matters need to be addressed properly. When it comes to actual micro-fabrication, there are certain challenges to be faced by any researcher at the lab or machinist at the job floor. Thus the major concerns and area for improvement in WEDM micro-fabrication can be categorized as follow:

1. Minimization of gap width
2. Ensuring better surface roughness
3. Improving material removal rate with reasonable surface characteristics

Research has been conducted to prove that point that better surface integrity can be achieved by optimizing the EDM process parameters [Rajurkar and Royo 1989; Laio and Woo, 1997; Ramulu et. al., 1997; Gatto and Iuliano, 1997]. To improve the EDM surface integrity, the size of craters need to be small [Qu and Albert, 2002]. This principally applies to die sinking EDM. But it is equally true for WEDM.

2.6.1 Kerf or Gap width

The kerf or gap width in WEDM consists of the diameter of the micro wire and two lateral discharge gaps. It is illustrated in the figure 2.3.

In WEDM gap width is defined as the additional gap created on each side of the wire after machining. It is measured by subtracting the wire diameter from the total gap width cut and then dividing the result by two. The gap width is a very important parameter when it comes to accurate machining. The machining path accuracy, the level of sophistication achievable in miniaturization depends on the minimum gap width possible. Thus for μWEDM it is a major challenge to reduce the gap width as much as possible. Studies on parameters are needed in detail for understanding the co-relation with gap width and how it can be further improved. Y. S. Liao et. al [1993] in their paper found that the gap width and surface roughness are mainly influence by pulse on time. But it was found out that only current on time, but also the applied energy influence the gap width. Also from the finding of other research work involved focused on the following parameters: Open circuit voltage, Peak current, Pulse duration or pulse on time and Wire tension.

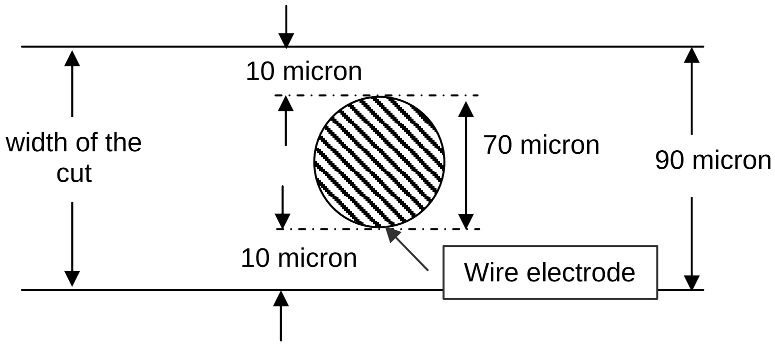


Figure 2.3: Illustration of Gap width

The dimensional accuracy of the kerf or gap width is very important in cutting micro parts. For WEDM, it is of practical need that the EDMed groove width should be predictable and under control. Depending on different machining condition, the groove width may vary. The internal corner radius to be produced in WEDM operations is also limited by the kerf. In order to have dimensional accuracy there is a need to know to control this EDM gap width. The input parameters of WEDM, like pulse on/off time, current intensity, open voltage, wire velocity affect the groove width.

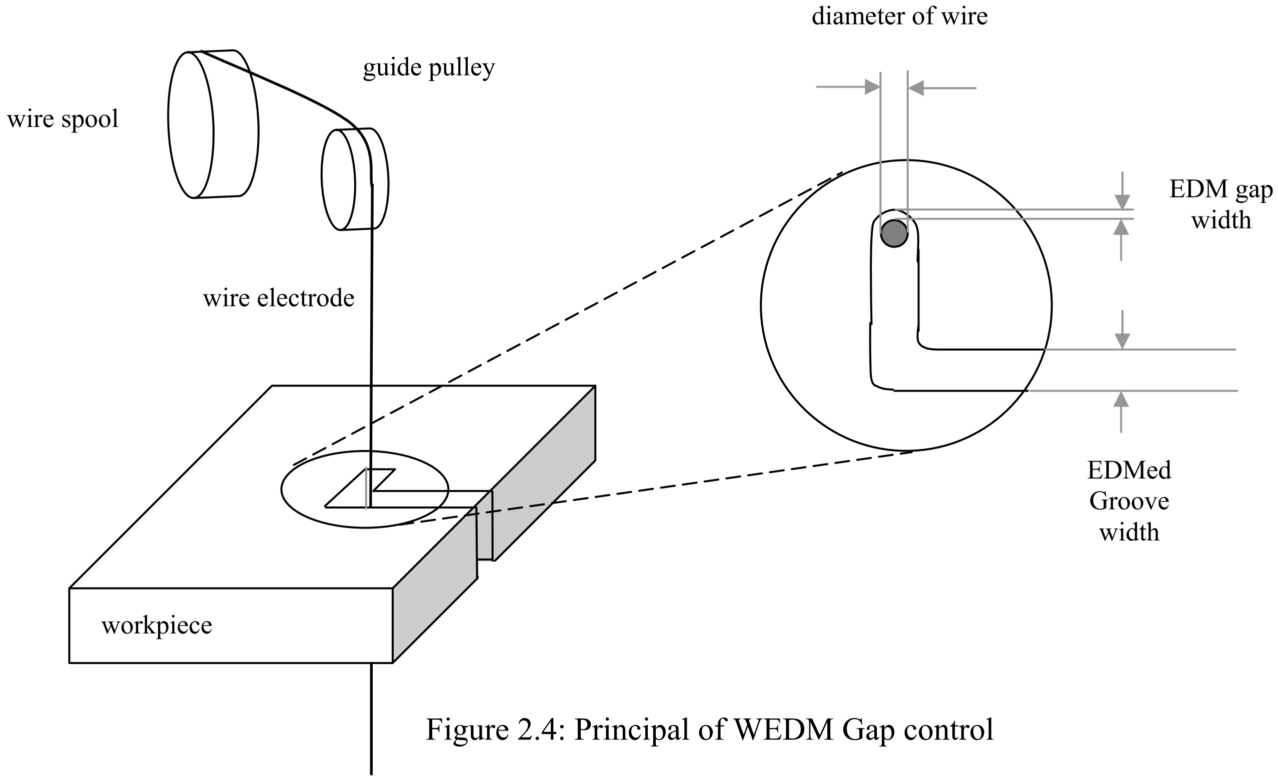


Figure 2.4: Principal of WEDM Gap control

The literature survey indicates that there are published works on the effect of machining parameters on MRR, surface roughness, cutting speed, wire rupture etc. But to the best of the knowledge of the author, there is very little research work on studying the effect of machining parameters on kerf or gap width in WEDM.

Nihat Tosun et. al [2004] have studied on kerf and material removal rate based on Taguchi Method. The experimental studies were conducted under varying pulse duration, open circuit voltage, wire speed and dielectric flushing pressure. They used commercial machine tool namely Sodick A320/EX21 EDM machine tool. CuZn37 Master brass wire with 250 micron wire diameter was used in the experiment. Thus the work can not be termed as µWEDM. The study was conduced on AISI 4140 steel. Parameter levels were 100 and 270 volt, pulse durations 0.3, 0.6 and 0.9 micron second, wire speeds 5, 8 and 12.5 m/min and flushing pressures was 6, 12 and 18

kg/cm^2. From their experimental results and statistical analysis they found that the most effective parameters with respect to kerf are open circuit voltage and T_{on} (pulse duration), whereas the effect of wire speed and dielectric flushing pressure on the kerf was insignificant. In terms of % values the effect on kerf are as follows:

Table 2.2: Significance of Major Parameters

Parameter	*% effect*
Open circuit voltage	63.44%
Pulse on time	28.7%
Dielectric flushing pressure	1.87%
Wire speed	0.83%

The problem of their analysis is that the choice of voltage level. They selected two levels of voltage, namely 100 and 270 which are quite far apart in terms of amplitude. Thus it is obvious that the significance of difference will be quite high in the observed machining characteristics. Instead of selecting such wide apart voltage values, it would be better if they could select a voltage value of 100 and 150 or 200 maximum to realize the effect in a more gradual fashion. Thus their analysis of open circuit voltage having an effect of more than 60% is partially biased from the design of experimental point of view.

In their paper Hwa Yan et. al. [2005] have machined Al_2O_3 p/6061 Al composite where pulse-on time, cutting speed, the width of slit and surface roughness were studied. Also location of wire breakage and the reason of it were explored. They found that the material removal rate, the surface roughness and width of the slit of cutting significantly depend on volume fraction of reinforcement. In the experimental investigation of gap width (width of slit) against pulse on time, it was found that the increasing pulse on time contribute to higher width of slit. But the result is very much influenced by the amount of reinforced particle in the work material since they very much influence the thermal conductivity and electrical conductivity of composite material.

2.6.2 Material removal rate

Material removal rate in WEDM is defined as the amount of material that is removed per unit time. Material removal rate is an indication of how fast the machining rate is. Since machining rate is very much related to the economic aspect, often it is a high preference objective to achieve. Thus a parameter that leads to higher material removal rate is important for the production. At the same time higher machining productivity must also be achieved with a desired accuracy and surface finish.

In their paper M. S. Hewidy et. al. [2005] have modeled the machining parameters of WEDM. They have used ELEKTTA MAXICUT434 CNC WEDM machine utilizing brass CuZn377 wire of diameter 250 micron and Inconel 601 workpiece. The effect of peak current, duty factor and wire tension are studied on volumetric material removal rate (VMRR). From experimental results the authors have found that that increase in peak current leads to the increase of the volumetric metal removal rate. This increase (in a range of 3 amp to 7 amp) is however diminishes after certain value (7 A). This results have been attributed to the fact that increase in peak current leads to the increase in the rate of the heat energy and hence in the rate of melting and evaporation. However after certain value, because of arcing, it decreases discharge number and machining efficiency, and subsequently VMRR. Also when flushing pressure increases, the tendency of arcing decrease, and increases the material removal rate.

VMRR generally increases with the increase of the duty factor (from 0.35 to 0.75) up to certain value (0.5) and then decreases with a further increase in duty factor. In this paper duty factor is defined as the ratio of pulse on time to total pulse on and off time. At higher value of duty factor, same heating temperature is applied for longer time. This causes an increase in the evaporation rate and gap bubbles number which while exploding causes removal of bigger volume of molten metal. Increase of MRR is continued with the increase of ejecting force until reaching a situation in which the ejecting force will have no more increase in VMRR since the molten metal decreases. From experimental graphs it is also clear that wear tension has almost no effect on wear ratio. In the complete range of wire tension from 7 to 9 Newton, the VMRR remain almost constant.

2.6.3 Surface Roughness

During each electrical discharge, intense heat is generated that causes local melting or even evaporation of the workpiece material. With each discharge a crater is formed on the workpiece. Some of the molten material is produced by the discharge is carried away by the dielectric circulation and the remaining melt re-solidifies to form an undulating terrain.

Ahmet Hascalyk and Ulas Caydas [2004] have studied surface roughness against open circuit voltage and dielectric fluid pressure. It was found that surface roughness increased when the pulse on time and open circuit voltage was increased. Because of greater discharge energy, the surface roughness is affected by on-time and open voltage. Again depending on the nature of the work material, the surface roughness varies. Because of higher thermal conductivity in annealed workpiece roughness value is higher than quenched/tempered samples. In this case, rapid dissipation of the heat through the sample happens instead of concentration on the surface.

When compared against different dielectric fluid pressure, surface roughness shows slightly decreasing trend with increasing pressure. This result is explained by the cooling effect and also increasing pressure helps the debris to be cleared out easily. The cutting performance with increasing dielectric fluid pressure improves because the particles in the machining gap are evacuated more efficiently.

B. Hwa Yan et. al. [2005] have examined the effect of pulse-on time on surface roughness. It is found that the surface roughness increases with increasing pulse-on time. As increasing pulse-on time generates high discharge energy, it widens and deepens discharge craters of workpiece surface. Also more reinforced particle in the workpiece contributes to poor surface integrity.

Y. S. Liao et. al. [2004] have found that the dominating factor affecting surface roughness is pulse on time, since the surface roughness depends on the size of spark crater. Most of the WEDM machine discharges current proportional to the current on time. The higher pulse on time imparts higher discharge energy that causes violent sparks and results in a deeper erosion crater on the surface. Accompanying the cooling process after the spilling of molten metal, residues remain at the periphery of the crater to form a rough surface.

M. S. Hewidy et. al. [2005] have studied surface roughness at different duty factors, wire tension and flushing water pressure. From experimental results it is demonstrated that the surface roughness slightly increases with the increase of peak current value up to a certain value and then vigorously increase with any increase of peak current. The authors have explained the phenomena by the fact that increase in peak current causes an increase in discharge heat energy at the point where the discharge take place. The overheated pool of molten metals evaporates forming gap bubbles that explode when the discharge ceases. This takes away molten metals away and forms crater on the surface. Successive discharges thus resulted in worse surface roughness. From SEM micrograph of WEDM surface at different peak current it is again demonstrated that the depth of the crater depend on the discharge heat energy which again on the peak current value.

The effect of duty factor on surface roughness demonstrated that with the increase with duty factor roughness slightly decreases. This is because increases of duty factor imply decrease in off time, which allow gas bubbles to decrease in number and to be smaller as a result of applying the heat energy for a shorter time. When the discharge ceases, these small gas bubbles will collapse containing lower pressure energy. The result is decrease in surface roughness. Wire tension effect on surface roughness demonstrated that with increasing tension, roughness decreased almost in a linear fashion. Since increase of wire tension minimizes the wire bending which leads to a dynamic stability condition and improves surface roughness. Surface roughness also decreased with increasing flushing water pressure to a certain limit after which the adverse effects of the force again produce worse roughness.

Y. S. Liao et. al. [1997] used SKD11 alloy steel (anode) as material and 0.25 mm diameter brass wire as electrode. Addition to pulse on time, table feed rate effect was also studied. From the analysis of the results, it was found that the surface roughness is mainly influenced by the pulse-on time. A larger table feed and a smaller pulse-on time is recommended by the authors for the reason that a longer pulse-on time will results in higher value of surface roughness. However, for table feed rate doesn’t affect roughness, even though it can not be increased without constraints because of the risk of wire breakage.

Chapter 3

DESIGN AND DEVELOPMENT

3.1 INTRODUCTION

One of the primal goals of this research work was to design and develop a WEDM device which can be used interchangeably on the CNC machine. The initial conceptualization of the device considered the existing setup of the CNC machine developed earlier with a target to incorporate both conventional and unconventional machining processes.

The design of the WEDM device was sent for manufacturing with subsequent modifications and improvements were made during the work for it to be operational. The CNC machine for which the device was designed to operate was part of a previous research work where the addition of the WEDM device is part of a continuos development effort.

3.2 DEVELOPMENT OF THE MICRO WEDM DEVICE

3.2.1 Identification of the need

For the WEDM device the prime requirements were:

a. The device has to be relatively compact so that it can be accommodated on the existing setup of the CNC machine
b. The design needs to function for micro wires of various diameters
c. There needs to be control of wire tension and wire run speed, preferably from a computer interface.

d. The device needs to have the provision to change the wire spool easily and conveniently
e. The wire needs to be guided precisely
f. The wire should have minimum vibration
g. There should be some mechanism that can help to maintain constant tension
h. There needs to be supply and re-circulation facility of dielectric fluid
i. There needs to have filtration of the dielectric fluid

3.2.2 Design considerations

After conceptualizing the device, several factors were considered during the development stage such as:

1. Since the space available on the CNC machine to mount the WEDM device is limited so a vertical design was conceptualized. The device is to be mounted on the XYZ stage of the CNC machine, vertically. The multi-purpose CNC machine has a maximum travel range of 210 mm in X direction, 110 mm in Y direction and 110 mm in Z direction.

2. There needs to be a mechanism through which the thin wire needs to be passed and where the actual machining will be performed. Since the whole device needs to move mostly in X and Y direction during machining, there needs to be room for this purpose. The source roller to be fitted on the top of the device and the actual cutting mechanism will happen at the bottom. In order to facilitate different diameter of micro wires, bearings are used instead of closed grooves. The bearings are considered so that

movement from the wire pool does not cause the wire to vibrate at the cutting area and thus deteriorating cutting condition.

3. Tension control of the fine wire is a critical requirement. For precision machining tension plays a pivotal role. Proper tension is again very much decisive in the case of wire breakage. For the tension various options were considered. For example electromagnetic brake is another option which has been used by Mu-Tian et. al. [2004] But after giving due consideration to the fact that an electromagnetic brake would be much more complex as a mechanism, it was ruled out. A simple yet novel mechanism for tension control is sought for the WEDM device.

4. WEDM technology uses wire electrode, which is discarded after use. For this reason another design consideration was to develop a mechanism which will enable removal of the used wire conveniently. One approach for wire disposal is to let the wire fall into a bucket or to collect it in a separate spool. Also the need for the ease of loading and changing the wire electrode is another issue to be given due consideration. As a result the source roller was designed to be placed on top of the device and the collector roller at the bottom part. The collector roller was secured with the main body in such a way that it could be taken out when it is full.

5. Wire transport is another feature that needs to be taken care of. From the wire source roller the wire has to be transferred to the actual machining section and then needs to be collected in the collector roller. To deal with problems such as vibration and wire breakage, wire transport is very crucial. Since the source roller is quite big in length,

the wire needs to shift its position while unwinding. To ensure that the wire runs smoothly some mid rollers were considered in the design.

6. The speed of the wire needs to be controlled using an independent motor. For this purpose a stepper motor is considered suitable because of the advantage that is gained regarding the control issues.

7. Dielectric fluid needs to be provided at the machining areas. For this a separate dielectric unit consisting of pump, filter, deionizer in case of water is needed. Submerge cutting operation is very important when it comes to WEDM. Thus a flushing device with filtering capability and a tank to accommodate the circulation of the active dielectric fluid was a requirement. Also the tank needs to be designed in such a way that corrosion can be avoided. When submerge operation is not required, the dielectric fluid needs to be drained out at faster rate. Complete sealing was another design consideration during the process.

8. The selection of material for the device was another important design consideration. Since the WEDM often utilize deionized water was dielectric medium, so there is a possibility of corrosion. To avoid corrosion materials such as acrylic, stainless steel, aluminum etc. are utilized.

9. In the case of power supply, the existing CNC machine has limited range, which hinders detail experimental studies. Thus an additional modification was sought to have a wider range of variable voltage or supply current for the WEDM operation.

3.2.3 Computer Aided Drawings of the WEDM Device

The drawings of the WEDM device were developed through the use of Solid works 2005 and can be found in Appendix A. A number of modifications and improvements were made to the drawings before finally sending it for fabrication.

3.3 APPLIED SOLUTION FOR THE WEDM DEVICE

3.3.1 Features of the designed WEDM device

The μWEDM device is designed as a vertically mounted on the CNC machine and it is interchangeable to replace other devices such as die sinking EDM or Turning device. The photograph and the CAD assembly and the configuration of the μWEDM device developed are shown in figures 3.1 and figure 3.2 respectively.

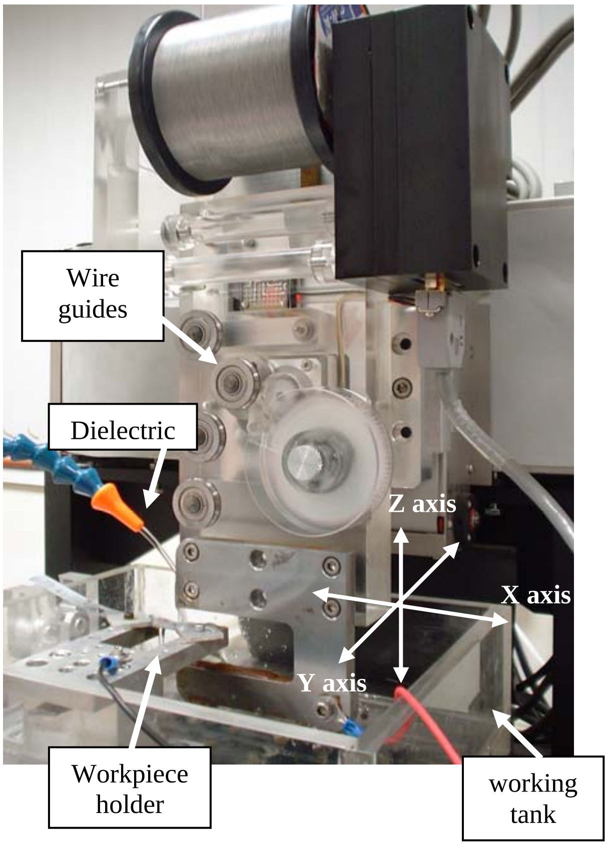


Figure 3.1: Photograph of μWEDM device

The major components of the device are as follows:

a. One source roller, which works as a supplier of wire electrode.
b. The left plate assembly that houses support bearing for the source roller as well as for mid rollers.

c. The right plate assembly houses the support bearing as well as the stepper motor and its circuitry to drive the source roller. This motor is responsible for controlling the tension on the wire.

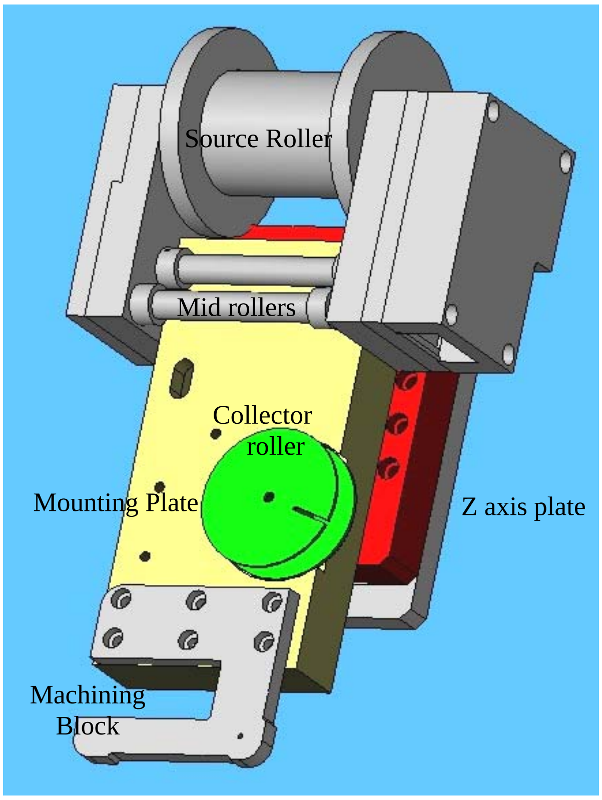


Figure 3.2: CAD drawing of the WEDM device

d. Mounting plate for housing the tension arm, rollers, circuitry for tension control, collector roller and stepper motor

e. Mid rollers for facilitating the movement of the wire.

f. 4 separate bearing rollers placed between mid rollers and machining block for guiding the wire.

g. Collector roller assembly is driven by a stepper motor. It is responsible to collect the worn wire to be disposed later. The collector roller has the facility to be taken out from the front portion to dispose of the wire. Also it has a wire-clamping flexibility.

h. Machining block for maneuvering the wire and facilitating the actual WEDM operation

i. Z plate to facilitate the mounting of the device to the CNC machine

3.3.2 Tension control for the wire

Tension of the micro wire is controlled with the help of a specially designed tension arm. The tension arm is coupled with bearing rollers. Thus when wire runs over it, because of the pull of the wire, the tension arm moves. The location of the arm had to be placed such that it would be able to create a constant tension throughout the wire path. As such, it was placed at the start of the path of the wire, just after it comes out from the wire spool. A spring mechanism together with a sensor circuit is used to maintain a constant value of the tension. The tension arm is connected with spring. In order to maintain the tension of the wire, a light sensitive sensor circuit was used.

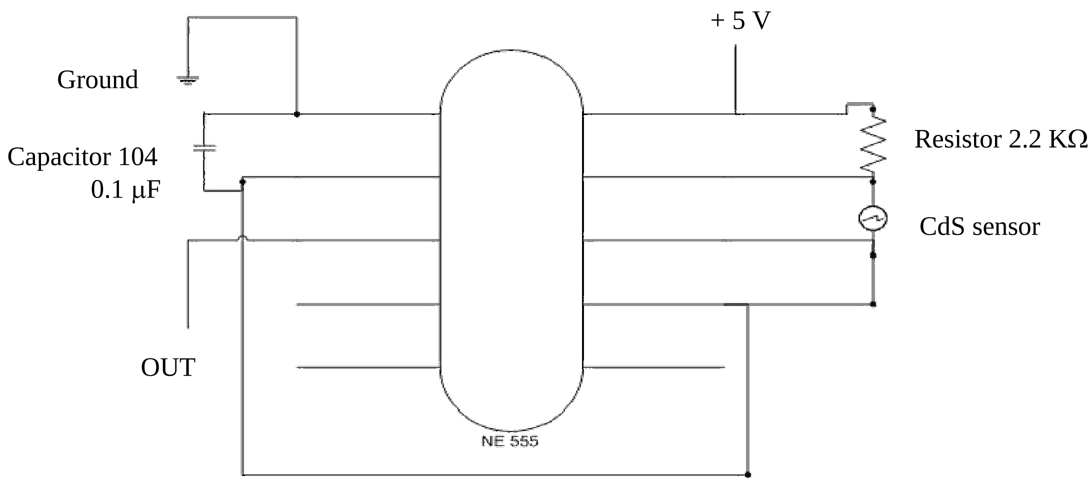


Figure 3.3: Tension arm sensor circuit

The designed sensor circuit was comprised of a NE555 Timer, a Cadmium Sulphide (CdS) Sensor, one resistor and one capacitor. The circuit diagram was designed and produced on a piece of PCB Board, and later inserted into the WEDM machine.

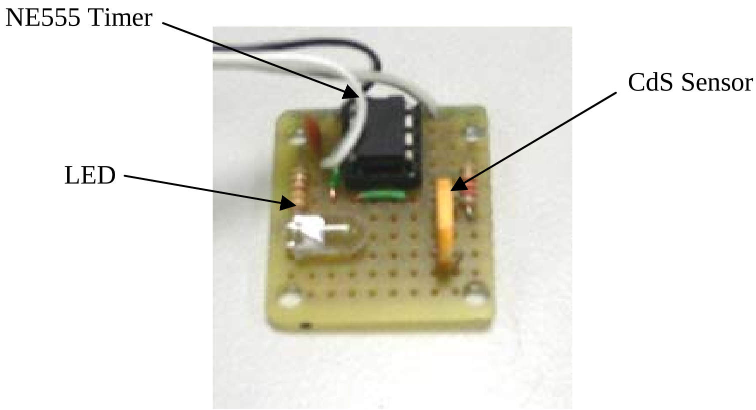


Figure 3.4: Photograph of the sensor circuit

The tension arm determines the amount of light emitted from the LED going to the CdS Sensor. With the use of a NE555 Timer, the amount of light falling onto the CdS sensor is converted into pulses and fed into the WEDM control system. The system then controls the wire feed motor speed accordingly driving the collector roller, hence maintaining a constant amount of tension in the wire. A 15 pin connection was also designed to connect the wire feed motor, wire collecting motor and the sensor circuit to the computer, so as to control these functions directly through the computer.

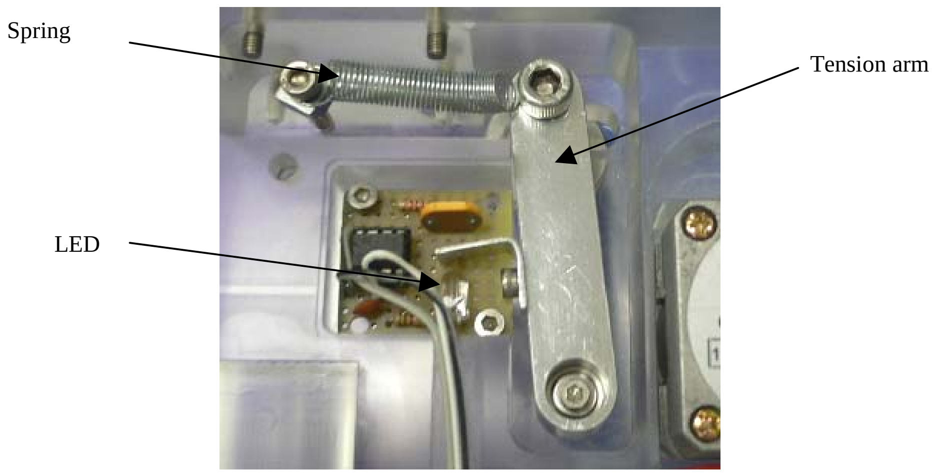


Figure 3.5: Photograph of the tension arm mechanism

The working principle for maintaining a constant tension in the wire is outlined below:

a) A tension level (corresponding to the sensitivity of the sensor) is first set through the software.

b) Once 'Wire Run' is activated on the computer, the wire collecting motor driving the collector roller is ON. The wire travels from the source roller along the wire path to the wire collector roller.

c) The tension of the wire is increased until the tension causes the tension arm to be pulled down; thus allowing more light to pass through the CdS (Cadmium sulfide) from the LED. CdS is actually a light variable resistor that's resistivity decreases with increasing illumination or light, thus allowing more current to flow.

d) Once the CdS receives enough light, the circuit turns on the wire feed motor, allowing more wire to travel faster. This thus reduces the tension, and the tension arm is retracted back allowing less light to pass the CdS.

e) Again when the CdS receives less light than its maximum amount, it turns off the wire feed motor again, increasing the tension of the wire.

f) Steps c) to e) are repeated rapidly, thus maintaining the desired tension of the wire.

3.3.3 Micro Wire cutting mechanism

The μWEDM device uses a novel cutting mechanism. One of the advantages of the WEDM machine is the ease of changing the supply of wire. This is done by locating the wire spool at the top of the machine and using its own weight to secure itself over the gears. If a different wire diameter is to be used, the wire spool can be taken off and changed with just a single screw. The wire comes down from the source roller and at first it comes over the two mid-rollers. These rollers help to support and help move the wire across the width of the source roller. After moving over the mid-rollers the wire continues to come down. Before it reaches the machining block at the bottom, the wire is passed over additional four rollers. Finally the wire runs over the edge of the machining block. The machining block is designed like a fork. The fork-like opening of the machining block (figure 3.7) is where WEDM operation occurs. Special groove is cut on the machining block to define the path of the micro wire. One end of the power supply is connected to the conductive machining block, which conduct the electricity supplied to

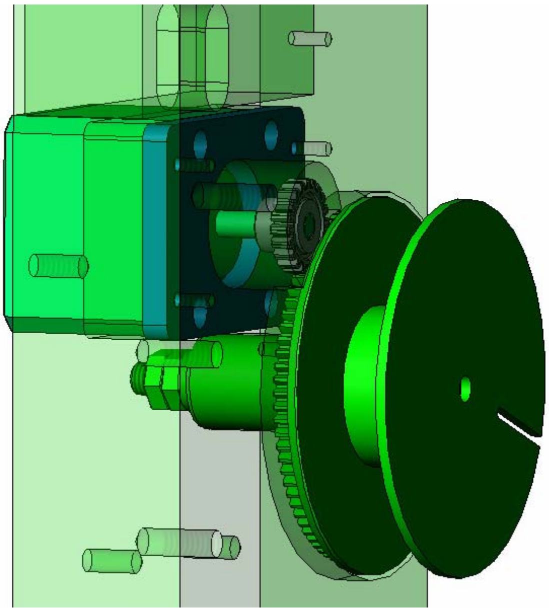


Figure 3.6: CAD illustration of speed control motor. A separate motor is used to control the speed of the wire. Coupled with gear and shaft this motor is connected to the wire collection wire pool

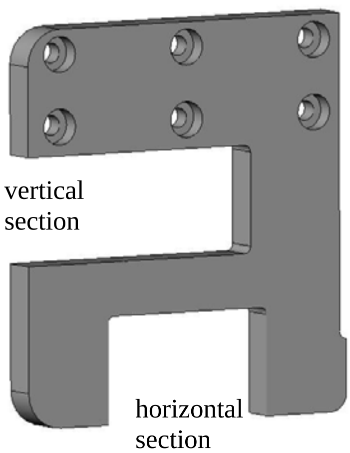


Figure 3.7: Fork-like structure of the machining block

the wire electrode. After the wire runs through the machining block it moves upward to the collector roller. From time to time, worn wire is taken out and discarded. The combined tension and wire run speed control is used for the cutting mechanism.

3.4 MODIFICATIONS AND IMPROVEMENT MADE TO THE WIRE-EDM MACHINE SETUP

3.4.1 Sensor Circuit

One of the prime challenges to design the sensor circuit is to make it small. There was size constraint in order to keep the device compact. The sensor circuit controls the motor of the wire feeding mechanism and ensures that the required wire tension level is always maintained.

A 15-pin circuit was designed and fabricated to link the 2 motors and the CdS sensor of the WEDM machine to the machining computer, so that the control of the wire tension and wire speed can be controlled directly from there.

3.4.2 WEDM Tank

For WEDM, submerge operation is very important. To facilitate submerged cutting operations, a bigger and durable tank was designed and fabricated. Initially the tank used for the WEDM operation was not capable of submerged operation and at the same time was smaller in size. The tank was designed using SolidWorks, and is made of acrylic. The new tank can also be used for other operations and devices such as the WEDG. Detailed drawings of the Tank can be found in the appendix A of this report.

The design considerations for the WEDM Tank are as follow:

1. To enable submerged cutting operations, and positioning of work piece holder
2. Tank must be completely sealed to prevent any dielectric from leaking out
3. Stopper design to allow fresh dielectric to flow out of the tank, maintaining a desired level (for submerge operation) and to facilitate good flushing conditions.
4. Compatible with other micro-machining operations, such as the EDG device

3.4.3 Curve program

The interface software developed does not support curved path for WEDM; only straight line programming is supported. But in practical application, many components require curve cutting. To overcome this limitation, a program was developed using C programming. The co-ordinates obtained from the program can be saved in notepad format, which can be easily pasted onto the WEDM machine platform. The program creates a curve based the principle that a curve is due to very discrete changes in steps. Therefore, arithmetic progression formula was used to generate the coordinates of the machine path co-ordinates.

3.5 ALGORITHM OF THE WEDM CONTROLLER AND OPERATION

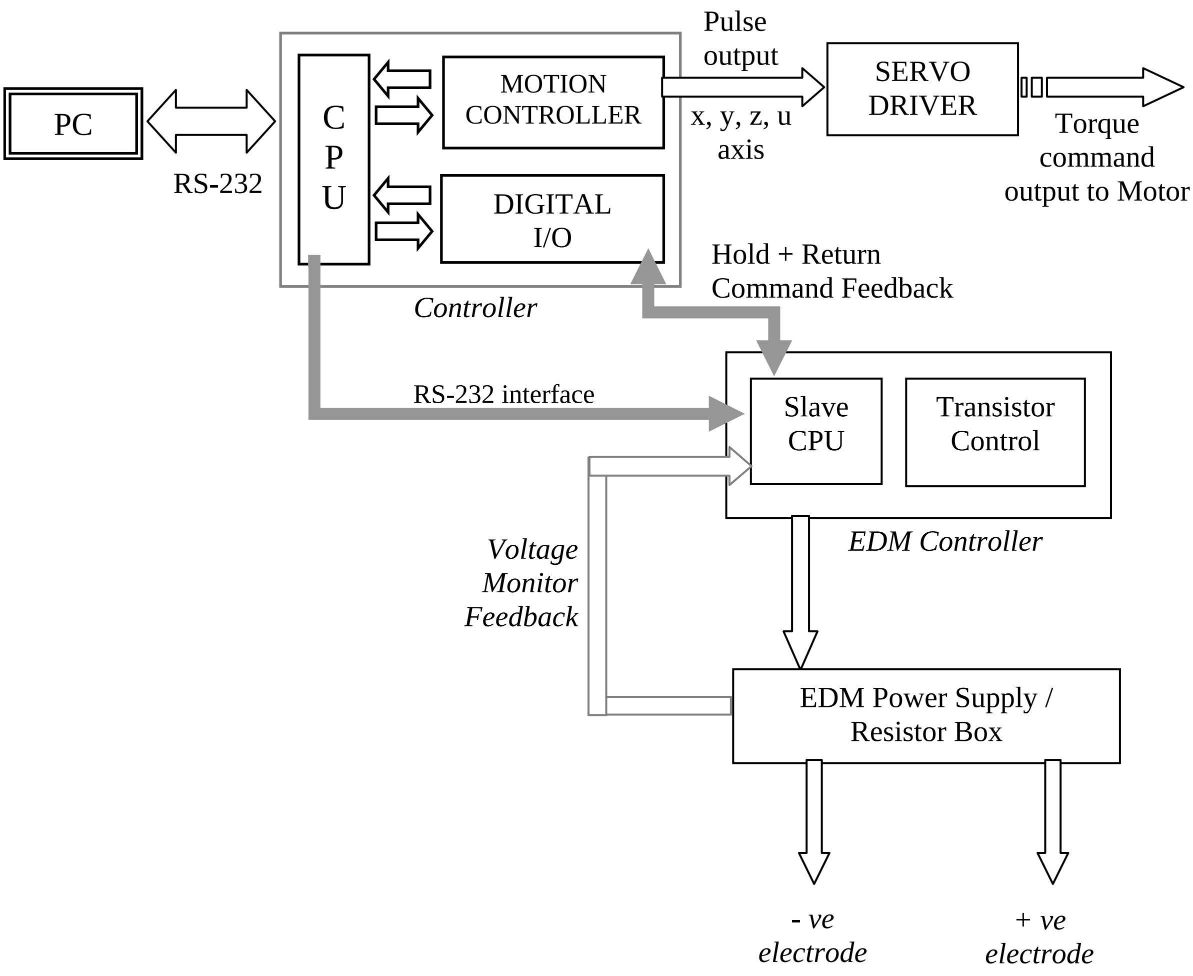


Figure 3.8: Block diagram of the WEDM controller signal / data flow

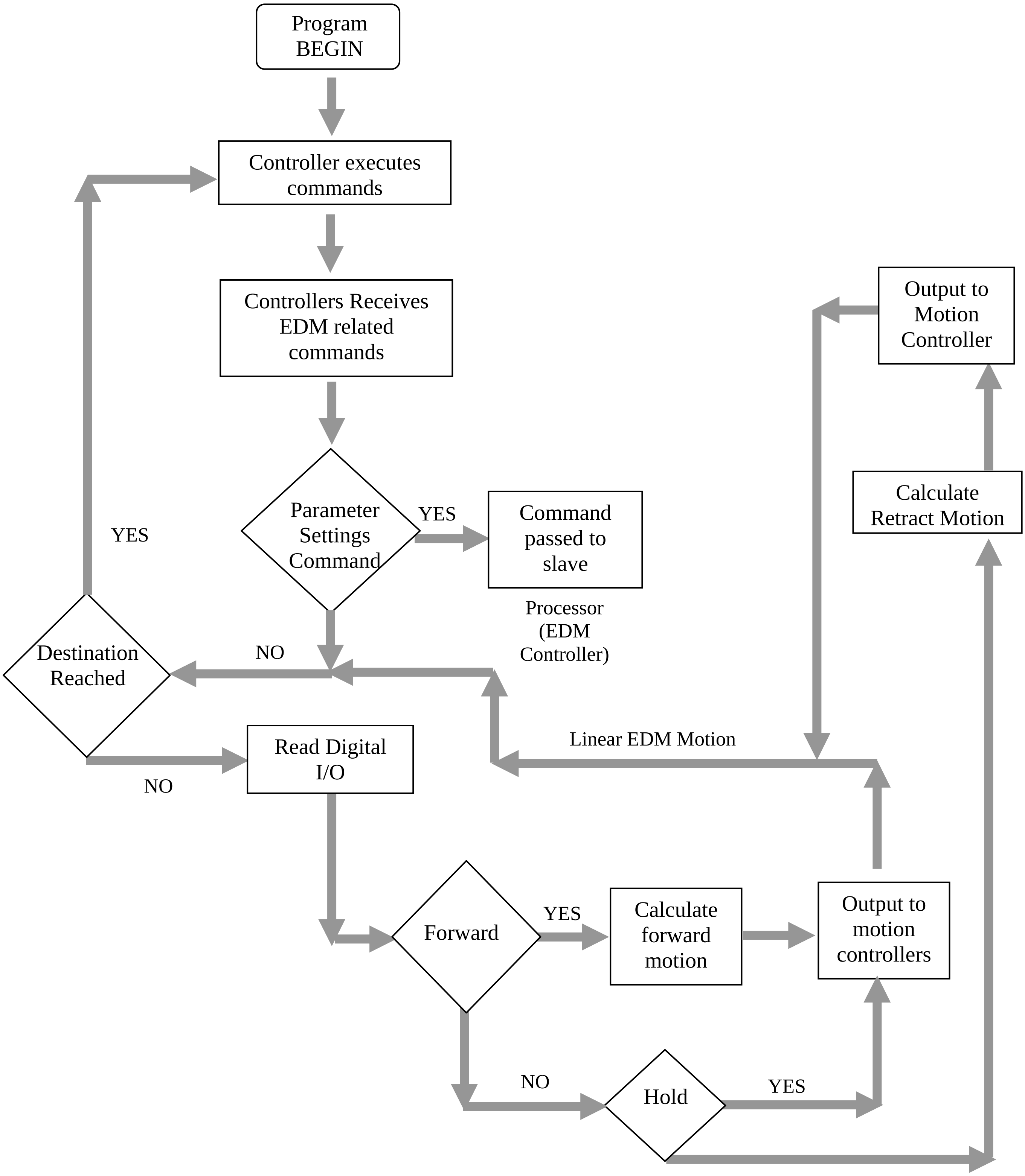


Figure 3.9: Algorithm for WEDM controller

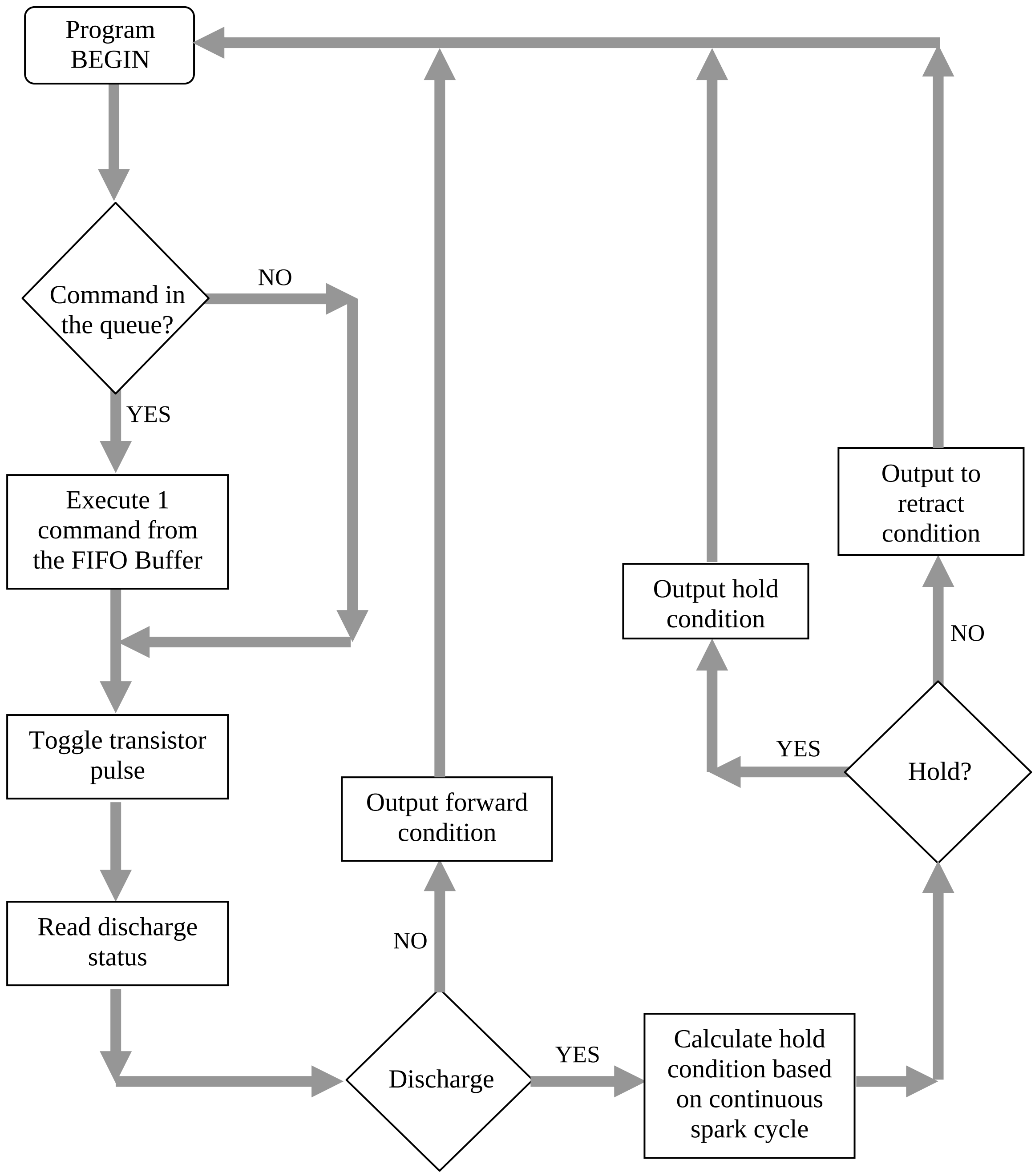


Figure 3.10: Algorithm for WEDM operation
(spark discharge and electrode movement)

Chapter 4

EXPERIMENTAL SETUPS

4.1 INTRODUCTION

In this study, many experiments have been carried out to realize the behavior of the newly developed WEDM device and also to investigate the optimal parameter. Different sets of parameters were tested. The device was installed on the existing CNC machine. All the experiments were conducted at MicroFabrication Lab, National University of Singapore. Details of the experiments and the experiment methods are described in the chapter.

4.2 EXPERIMENTAL DETAILS

Investigation on the effect of the parameters of WEDM was done by cutting through specimens of stainless steel sheets varying in thickness from 0.02 to 3 mm. Slots of about 0.5 up to 2 mm were cut and analyzed under different optical measuring instruments. Mostly characteristics of the EDMed surface, roughness and the gap width were checked during the experiments. Calculations such as material removal rate (MRR) and Spark Energy were made after collecting the data.

Table 4.1: Experimental details at a glance

Specimen material	SUS 304 Stainless Steel, Mild Steel, Tool Steel and Silicon
Thickness of material	0.02 – 3 mm
Type of wire electrode	Tungsten wire (Agie Charmilles)
Wire diameters	30, 50, 70 µm
Dielectric fluid	Deionised water, EDM oil, air
Cooling method	Normal flushing, submerged flushing

4.2.1 Experimental Setup

The main parts of the setup include the interfaced PC, the attached WEDM device, workpiece attachment mechanism, a set of discharge circuits and controllers, WEDM Tank and the workpiece. There is also control software capable of CNC programming and ability to change the parameters. Figure 4.1 shows the μWEDM device. Different components and general description of the experimental setup is given in figure 4.2.

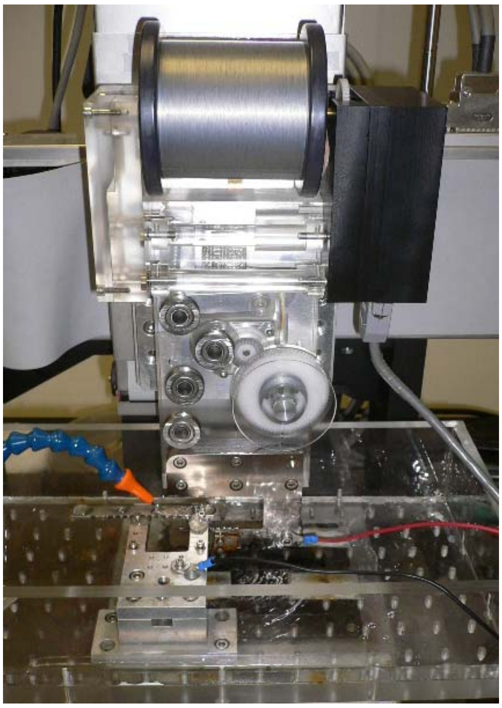


Figure 4.1: Photograph of the WEDM device attached to the multi-purpose machine tool

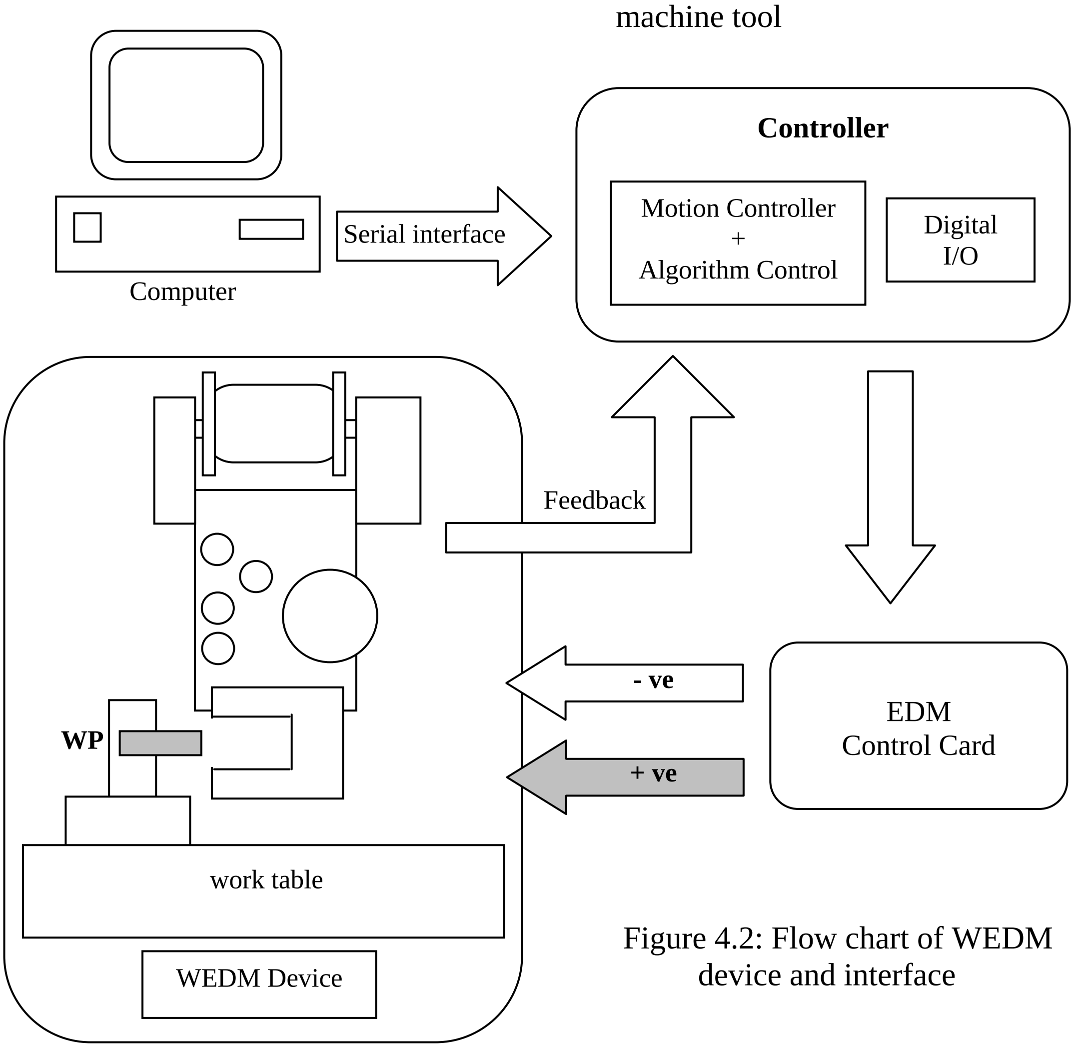


Figure 4.2: Flow chart of WEDM device and interface

4.2.2 CNC Machine Tool

The CNC machine is designed in a modular fashion. Thus different attachment for μWEDM, WEDG, ECM, Turning, Milling and drilling can be added to it as interchangeable device. The μWEDM device is a vertically mounted on the CNC machine.

Specifications of the Multi Process CNC machine tool are:

- Size: 560 mm (W) x 600 mm (D) x 660 mm (H)
- Maximum travel range: 210 mm (X) x 110 mm (Y) x 110 mm (Z)
- Each axis has optical linear scale with the resolution of 0.1 μm, and full closed feedback control ensured accuracy of sub-micron.

4.2.3 Electrode Material

Previously in WEDM, copper and brass were the major materials used as wire electrode. But with diverse applications of WEDM, other materials such as molybdenum or tungsten are increasingly used. Also special coated wire materials such as coated copper core wire, brass cored wire, silver coated brass wire are getting increasingly popular.

Table 4.2: Application based on electrode wire material

Wire material	*Application*
Brass	All metals, holes
Copper	All metals, holes
Tungsten	All metals (specially refractory metals), small slots or holes
Copper-Tungsten	All metals, carbide slots, thin slots
Steel	Nonferrous, holes
Molybdenum	Refractory, holes

In the current work wire electrode of Tungsten material was used. 3 different diameter of tungsten wire, such as 30, 50 and 70 μm wire were utilized. Tungsten wire was selected because of its high tensile strength (which is the ability to resist stretching and breaking), which is especially important since wires of very small diameter are to be used in micro fabrication. It is also fairly conductive, and has good fracture resistance that translates into better wire toughness.

Table 4.3: Properties of Tungsten

Property	*Unit*	*Value*
Density of solid	kg/m^3	19250
Young's modulus	Gpa	411
Bulk modulus	Gpa	310
Brinell hardness	MN/m^2	2570
Electrical resistivity	Ohm/m	$5x10^{-8}$
Thermal Conductivity	W/cmK	1.74
Electrical Conductivity	/cm ohm	0.189106

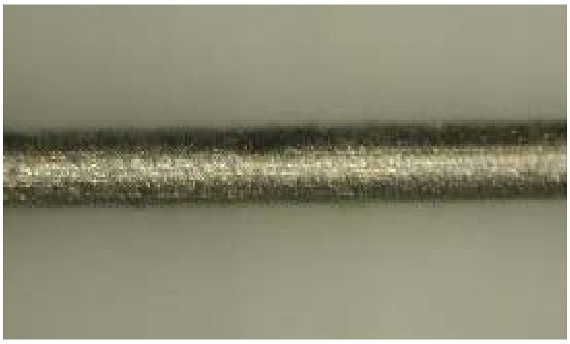


Figure 4.3: Tungsten wire before machining

Figure 4.4: Tungsten wire after machining. The wear of the wire is clearly visible in the photograph.

A point to take note is that the diameter of the tungsten wire used during the experiment was found to be actually larger than the specified diameter. For example, by using Keyence to measure the diameter of 30 and 70 µm wires, a larger value was found in some sections of a strand of wire. Therefore, a better gap width might actually be achieved had the diameter of the wire were more consistent.

Throughout the experimental phase of the research work, tungsten of various diameters had been used. In order to obtain an accurate view of the results, the diameter of the wire was check for accuracy using Keyence microscope. Under Keyence, the diameter of an uncut strand of 30 µm wire was found to be about 34 µm, while the diameter for a used wire was about 24.3 µm after machining. The accuracy of the diameter of the tungsten wires were also larger by 3 to 4 µm, thus affecting the best gap width that can be obtained in this work. Similar results were obtained using the 70 µm wire, with the diameter of the wire larger at 74 µm.

4.2.4 Workpiece Material

In this experiment SUS 304 grade stainless steel is used as it is the most versatile and most widely used. Stainless steel has seen many applications in the manufacturing industry, particularly in areas where corrosion and high-strength needs are required. Due to its high hardenability, superior mechanical property and corrosion resistance martensitic stainless steel is widely used for plastic molds, precision mechanical parts, and surgical tools [Koenig, 1990]. It has excellent forming and welding characteristics. The balanced austenitic structure of Grade 304 enables it to be severely deep drawn without intermediate annealing, which has made this grade dominant in the manufacture of drawn stainless parts. Typical applications include food processing equipment, chemical containers, surgical tools or most applications that require good anti-corrosive properties.

Table 4.4: Properties of stainless steel 304

Tensile Strength (MPa) min	*Yield Strength (MPa) min*	*Elongation (% in 50mm) min*	*Rockwell B (HR B) max*	*Brinell Hardness (HB) max*	*Electrical Resistivity (nΩ.m)*
515	205	40%	92	201	720

Table 4.5: Composition of stainless steel

C	*Mn*	*Si*	*P*	*S*	*Cr*	*Ni*	*N*
0.08	2.0	0.75	0.045	0.030	20.0	10.5	0.10

Since the major focus in the research is to study the performance of the newly developed WEDM machine apart from stainless steel, other grades of steel such as mild steel and tool steel were also used. To investigate the machining performance on low conductive material, silicon wafer was also used as workpiece material.

4.2.5 Dielectric

Dielectric is very important when it comes to WEDM and also for conventional die sinking EDM. The dielectric used in the experiments were deionized water and EDM oil. Two kinds of dielectric were used for comparison purpose. Also two mode of flushing were used such as normal low pressure flushing and submerged flushing. At the same time results were obtained by EDMing in air only.

4.3 MACHINING PARAMETERS

The machining was performed with various combinations of current, voltage, spark on time, spark off time, open, short values to investigate the gap width, machining time and surface roughness. At the same time the machining was conducted in air, deionized water and oil. The various combinations of the cutting parameter values available during the research are listed in table 3.5.

Table 4.6: Available Machining Parameters

Parameter	*Range*
Voltage	Initially fixed at 150 and 75 volt. Later a variable transformer was added that allowed various voltages ranged from 70 volt to 150 volt.
Resistance	4 level of resistances

	6.8 ohm, 15 ohm, 33 ohm and 100 ohm
Current on time	3 to 150 micro-second
Current off time	6 to 300 micro-second
Short	2 to 50
Open	5 to 50
Tension	1% to 50%
Speed	1% to 50%

4.4 MEASUREMENT APPARATUS

4.4.1 Gap Width

Gap width is observed under VHX Digital Microscope and STM6 measuring microscope. Accurately measuring the gap width was difficult since the gap width was not uniform from the bottom plane to top plane. Since at higher magnification, a little difference of height could change the focus, at different height different gap width was visible. Thus an average estimation was taken after calculating gap width from a number of places. To minimize inaccuracy, gap width measurement was taken on both VHX digital microscope (VH-Z450) which has magnification from 450 to 1000 times, and also on STM6 with comparatively lower magnification. The VHX microscope has the ability to give 3D surface profile as well, which was utilized to visualize the machined surface. It also had the ability to capture the image directly to the computer and offer on-screen measurement feature. The STM6 microscope was fitted with digital camera and also on-machine measurement system.

For closer inspection of the surface for heat affected zone, understanding the nature of the debris, amount of material transfer from wire electrode to the workpiece, EDX and SEM were used. By using the SEM it was possible to observe the edges of machined surface at a very high magnification.

4.4.2 Study of vibration

Since the wire used in the experiment is 70 micron to 30 micron in diameter, the vibration of the wire was not an easy phenomenon to detect with naked eye. Still the vibration, no matter how much, has its effect on the accuracy on the machined surface, specially on the geometry of the machining path. Thus to realize how much vibration is actually affecting the cutting mechanism was important.

For this purpose a high-speed camera was employed. The camera used was The Photron Ultima APX (figure 4.5). The APX provides full resolution images up to 2,000 fps, and reduced resolution all the way up to a phenomenal 120,000 fps. The video was captured at lower frame rate for substantial amount of time. Because of very small area and problem with illumination, not very high frame rate could be used. Higher frame rate required very high powered light which was difficult because of extreme heat generated. Such heat affects the WEDM machining process. So mostly for a better image a frame rate of 125 or 200 frames per speed was chosen. It is relatively low but enough to observe the vibration of wire at different tension.

Figure 4.5: High speed camera utilized in the research work for capturing the vibration of the wire electrode

Different parameters such as wire speed, wire tension and also machining parameters such as spark on time, current etc. were varied during the capture of video. The videos are stored in CD.

4.4.3 Study of spark

To monitor the overall sparking conditions, short circuiting and actual spark on/off time an oscilloscope aided with electronic data recorder was used. The characteristics of the spark signals provide a good indication about whether the machining is favorable or not. This could aid to determine the optimal parameters for machining.

4.4.4 Surface roughness

For measurement of surface roughness, Stylus 120 Probe Tip by Taylor Hobson was used. The instrument directly gives surface roughness (Ra) in terms of micron meter. The device was able to calculate the roughness value automatically. The data obtained from the physical scanning of the surface of interest, the interface computer software could plot the roughness curve directly on screen. The roughness values were measured as RMS.

Chapter 5

ANALYSIS OF EXPERIMENTAL RESULTS

5.1 INTRODUCTION

In this chapter the analysis of the experimental data are conducted. Different data obtained from the WEDM parameter under study are analyzed by plotting the data. Parameters that are studied are:

- Voltage
- Current
- Energy
- Spark on and off time
- EDM Speed
- Wire Speed
- Wire Tension
- Dielectric fluid

5.2 EFFECT OF VOLTAGE ON MACHINING CHARACTERISTICS

For WEDM voltage is an important parameter which was studied in order to investigate its effect on the machined surface. The voltage determines the discharge energy that is available in the spark erosion process of removing the material. As the voltage increase, more energy is available in the sparking and therefore more material is removed during the machining process. At the same time the high spark energy also results in a higher occurrence of molten material that may have other effect on the machined surface. More molten material may introduce more gap width and higher surface roughness.

5.2.1 On Gap width

The effect of voltage on gap width is show in figure 5.1. The voltage was varied from 80 volt up to 150 volt. The trend of increasing gap width with increasing voltage is visible from the data collected. Higher voltage in general increases the gap width and also causes over-cut. The wire diameter used was of 70 micron meter. For such the best gap width was obtained for minimum voltage of 80 volt and the gap width was 15.38 micron meter.

Higher open-circuit voltage generally increases the gap width and over-cut. Keeping all other factors constant, an increase in the breakdown voltage will also result in increased, energy per spark. Consequently, material removal rate increases, resulting bigger and deeper crater on the surface; and hence, poor surface finish. As a general observation with increasing voltage, machining rate increases and too high voltage causes unfavorable concentration of discharge due to insufficient cooling of material. So material removal rate will decrease, and wear will increase.

The selection of supply voltage is a compromise between several factors; for example, machining speed, surface finish etc. For micro machining the voltage should be kept at minimum to ensure the surface finish is good, but again the machining speed may not be so satisfactory.

Table 5.1: Fixed parameters

Wire Speed, Tension	*Voltage Volt*	T_{on}, T_{off} μs	*Res.* Ω	*EDM Speed* μ/s	*Short*	*Open*
30%, 40%	80	30, 30	100	5	20	10

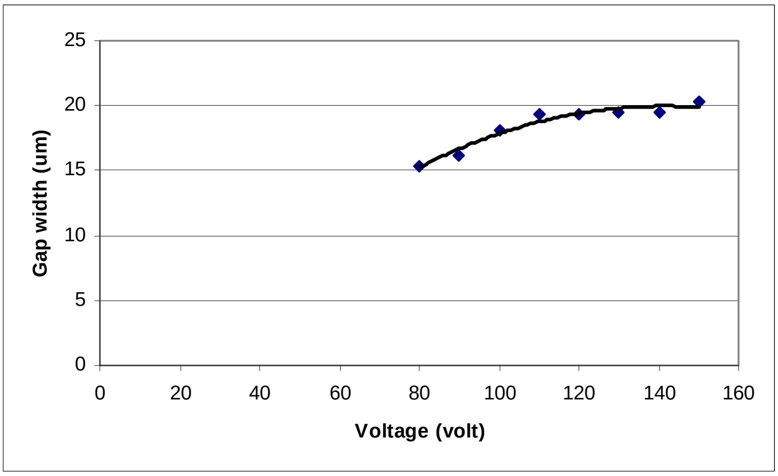


Figure 5.1: Effect of voltage on gap width, Resistance 100 ohm

For further investigation on the gap width further experiments were conducted, with reduced T_{off} time but higher current (setting the resistance lower) and E value.

Comparing to figure 5.1 and figure 5.2 two different patterns was observed. In figure 4.1 the gap width increased almost constantly as the voltage increased. Whereas in figure 4.2 it seems that the gap width initially was high, obtained optimum value at certain range and then again increased. This later phenomena can be explained by the fact that since less resistances are used, so the intensity of the sparks are higher when voltage increase as compared to figure 4.1 where resistance was high (100 ohm). At higher resistance, the intensity was low already, as a result the effect of increasing voltage was gradual. At high intensity current (figure 5.2), the gap width are varied and it seemed that 100 to 130 volt yields the best gap width (minimum). For example at 120 volt a gap width of 2 micron meter was achieved which was a very significant result.

Table 5.2: Fixed parameters

Wire Speed	*Wire Tension*	T_{on}, T_{off} μs	*Res.* Ω	*EDM Speed* μ/s	*Short*	*Open*
30%	40%	15, 12	33	10	5	5

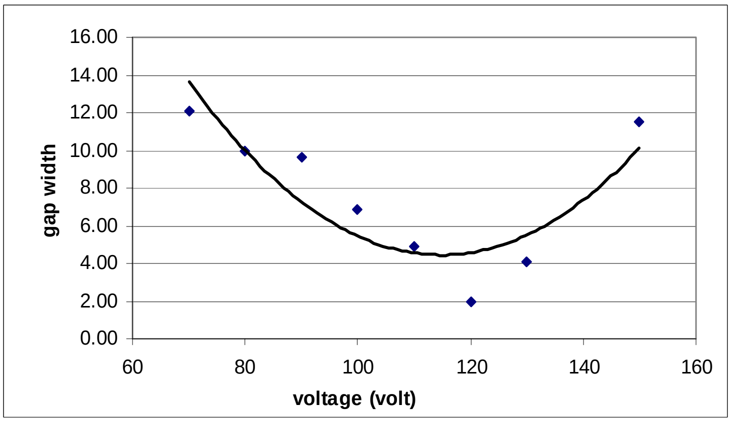


Figure 5.2: Effect of voltage on gap width on lower resistance of 33 ohm

5.2.2 Machining time

The effect on machining time is demonstrated in figure 5.3 and figure 5.4. As the voltage level increase the machining time reduces. This is due to the increase of energy available in the spark to accelerate the material removal. There are certain amounts of fluctuation in the gathered data because of unpredictable nature of the spark, short circuiting etc. Thus for material removal rate it can be easily concluded that for higher machining rate, voltage should be selected as high as possible, provided that the wire doesn't break due to high energy.

Table 5.3: Fixed parameters

Wire Speed	*Wire Tension*	*T_{on}, T_{off} μs*	*Res. Ω*	*EDM Speed, μ/s*	*Short*	*Open*
20%	40%	15, 30	33	20	5	5

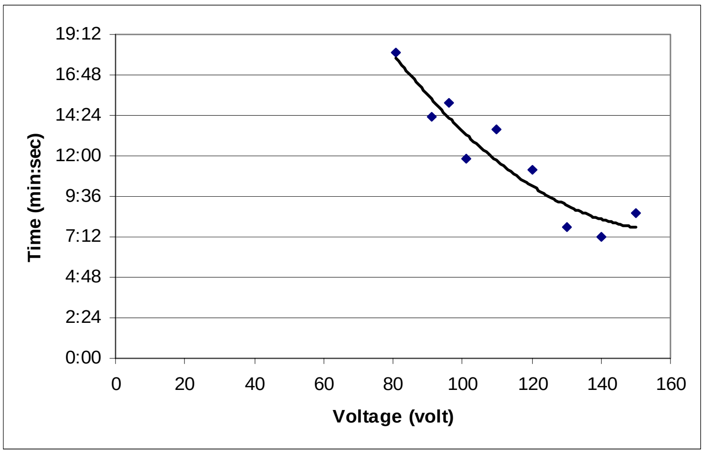


Figure 5.3: Effect of voltage on machining time, Resistance 33 ohm, Ton 15 micro-sec

Another set of experimental results at different resistance value and other fixed parameter is presented. Here also it is verified that for higher machining time there is no other choice but to select for maximum voltage allowable from the machine.

Table 5.4: Fixed parameters

Wire Speed	*Wire Tension*	T_{on}, T_{off} μs	*Res.* Ω	*EDM Speed* μ/s	*Short*	*Open*
30%	40%	15, 30	100	5	10	20

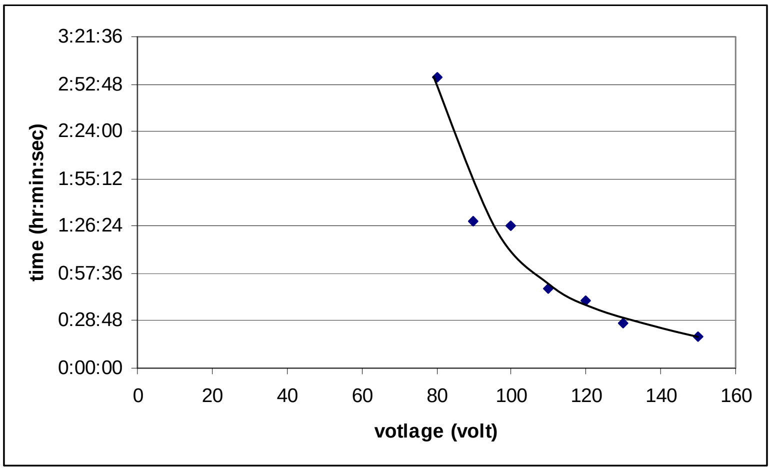


Figure 5.4: Effect of voltage on time, Resistance 100 ohm

Another set of data on machining time are also presented here. This experimental data was obtained for another set of fixed parameters. The basic experimental findings are similar and confirm the previous results that with increasing voltage the machining time decreases almost linearly. Comparing between figure 5.4 and 5.5 it is evident that a change in current due to resistance can reduce the machining time dramatically.

Table 5.5: Fixed parameters

Wire Speed	*Wire Tension*	T_{on}, T_{off} μs	*Res.* Ω	*EDM Speed* μ/s	*Short*	*Open*
30%	40%	15, 12	33	10	5	5

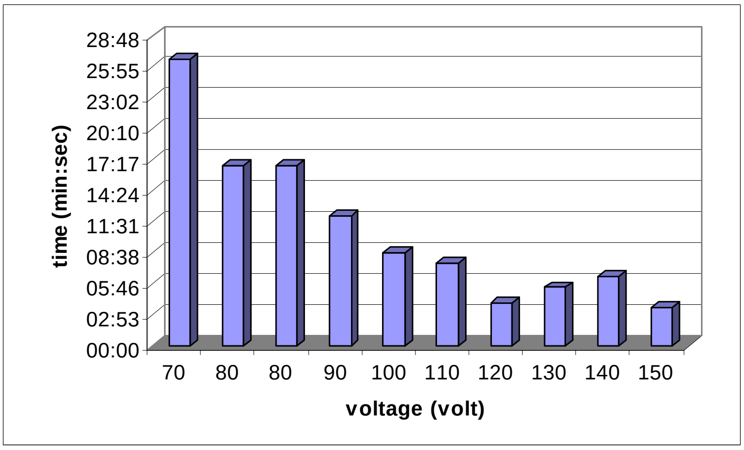


Figure 5.5: Voltage against time at higher current, Resistance 33 ohm

5.2.3 Material Removal Rate

Machining time when incorporated with the amount of material removed, another term Material Removal Rate (MRR) can be used. Although the main purpose of machining time and material removal rate is similar; two terms can give two different results in WEDM. Because of parameter effect, two experiments can have the same machining time, but different material removal rate. For example, even if the machining time is the same, because of more material removed – the MRR value becomes different. And the amount of material removed depends on the energy intensity in the spark, thus depends on parameter setting. MRR was studied against different voltage settings. It is found from the experimental graph that material removal rate increases with voltage and the trend is quite linear.

Table 5.6: Fixed Parameters

Wire Speed	*Wire Tension*	T_{on}, T_{off} μs	*Res.* Ω	*EDM Speed* μ/s	*Short*	*Open*
40%	40%	30, 30	33	10	12	8

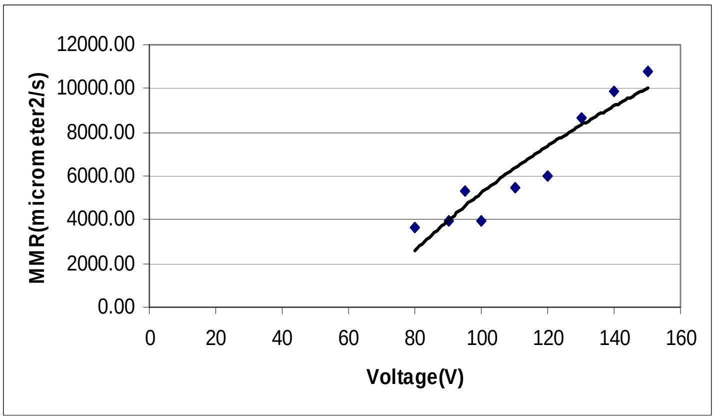


Figure 5.6: Effect of voltage on material removal rate

5.2.4 Surface Roughness

Surface roughness is an important indicator which translates how good the surface finish is. The surface roughness measured for difference values of voltage indicate that there is a particular area or region for which better surface roughness can be achieved. From the experimental graph it seems that optimal value of voltage for surface roughness was achieved in the range of 110 to 130. But this again depends on the wire diameter and other factors.

Table 5.7: Fixed Parameters

Wire Speed	*Wire Tension*	*T_{on}, T_{off} μs*	*Res. Ω*	*EDM Speed μ/s*	*Short*	*Open*
40%	40%	30, 30	33 and 100	10	12	8

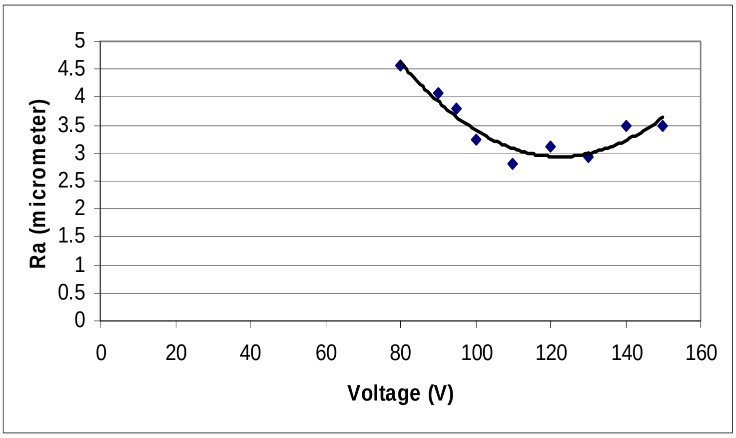


Figure 5.7: Surface roughness (Ra) against applied voltage, Resistance 33 ohm

This graph was obtained at higher spark energy, since the resistance value was set at 33 ohm. Later in other experiments surface roughness at lower energy level was obtained. It was found that the roughness improves by significant amount when spark energy is lowered by setting the resistance at higher value (100 ohm). When the resistance is reduce to 100 ohm, the surface best roughness obtained was below 0.5 micron. Here again the same trend as figure 5.7 was obtained. The surface roughness initially was worse, then gradually decreased until in the range of 110 to 130, the best roughness values were obtained. Then again the surface roughness value started to climb upward with increasing voltage.

Table 5.8: Fixed Parameters

Wire Speed	*Wire Tension*	*T_{on}, T_{off} μs*	*Res. Ω*	*EDM Speed, μ/s*	*Short*	*Open*
40%	40%	30, 30	100	10	12	8

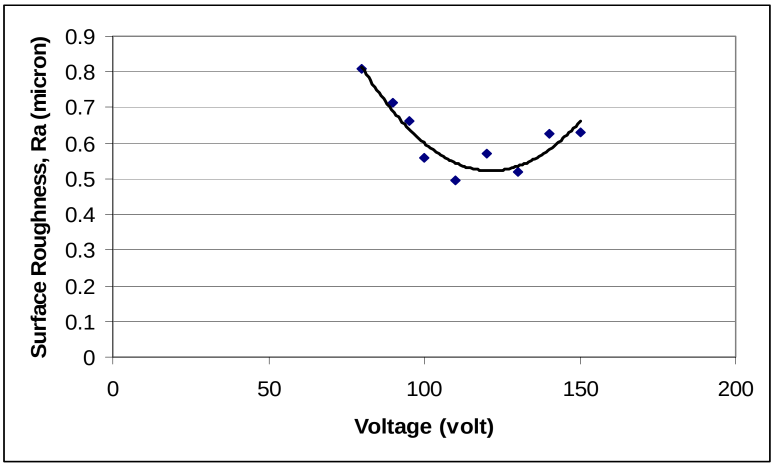


Figure 5.8: Surface roughness (Ra) against applied voltage, Resistance 100 ohm

5.3 EFFECT OF CURRENT AND ENERGY

The current is an important parameter in WEDM. This determines the amount of power used in discharge machining, measured in units of amperage. The maximum amount of current is mainly governed by the surface area of the cut – the greater the amount of surface area, the more power or amperage that can be applied. Generally higher current is used in roughing operations and in cavities with large surface areas.

5.3.1 Machining Time

Machining time is influenced by the amount of current or the applied energy. From experimental graph it was observed that with decreasing current (increasing resistance), the machining time increases almost proportionally. When the resistance was lowest (6.8 ohm), corresponding current was highest (11.765 amp)

Table 5.9: Fixed Parameters

Wire Speed	*Wire Tension*	T_{on}, T_{off} μs	*Voltage Volt*	*EDM Speed* μ/s	*Short*	*Open*
40%	40%	30, 30	80	20	10	5

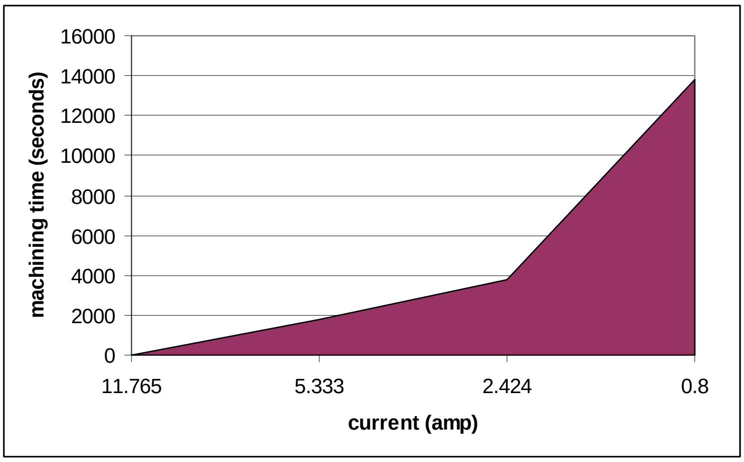


Figure 5.9: Effect of current on machining time

5.3.2 Energy Aspect

In the current WEDM power supply, the amount of energy or current was regulated by selecting different resistance and voltage. There were 4 fixed resistances on the machine which by changing, for 1 particular set voltage, different current values were obtained. The lower value of R leads to a higher discharge energy.

The amount of energy impart on the workpiece during machining is very important. In previous literature a concept of specific discharge energy has been discussed [Liao and Yu, 2004]. But the idea is not clear and specific enough to be applied in case of WEDM.

On repeated experiments it was observed that the machining time was not consistent with current only. Careful observation revealed that the spark on time also influence the result. For this reason the effect of the energy, consisting of voltage, current and spark on time was incorporated in a different set of experiments to find out whether current alone or energy have more consistent effect on the machining time.

Table 5.10: Fixed Parameters

Wire Speed	*Wire Tension*	T_{on}, T_{off} μs	*Voltage Volt*	*EDM Speed* μ/s	*Short*	*Open*
15%	25%	18, 36	150	10	10	30

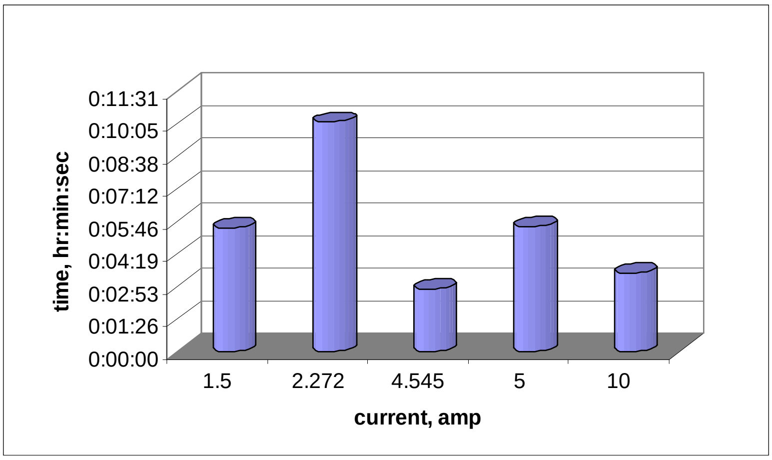


Figure 5.10: Relation with current and machining time

In the above graph, the time taken with current 0.75 and 11.029 are too high when compared to other values. So those values were left out from the graph. It is interesting to note that although in literature it has been noted that current is one of the most important factors for WEDM operation; we find here that the effect of voltage and spark on time is more profound than current alone. In this experiment, different combination of Voltage and Resistance were tested. The WEDM machine initially had two voltage settings, 150 and 75 volt along with four resistances, 6.8, 15, 33 and 100 ohm. Using these combinations of voltage and resistance we get 8 value of current.

As we can observe from the graph that the time taken to machine a particular amount is mostly affected by the voltage. When the applied voltage is high (150 volt), the machining time is consistently low when compared with low voltage (75 volt). The explanation of the phenomena can be described with the energy equation.

Here, Energy = Joule or Watt.sec = V x I x T_{on}

Where, I = current, V= voltage, T_{on} = current on time

By plotting the machining time against the energy applied, it is clear that the machining time depends on the actual energy input.

Table 5.11: Fixed Parameters

Wire Speed	*Wire Tension*	*T_{on}, T_{off} μs*	*Voltage Volt*	*EDM Speed μ/s*	*Short*	*Open*
15%	25%	18, 36	150	10	10	30

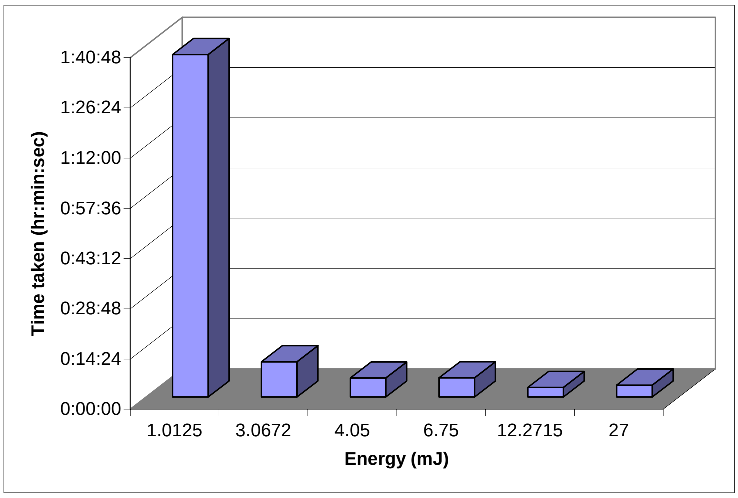


Figure 5.11: Plot of machining time against spark energy

So to calculate the expected WEDM time, one must consider energy, rather than current or voltage separately.

5.3.3 Energy and Gap width

The effect of current or energy on gap width is studied as well. From the figure 5.12 it is clear that the middle range of the energy is favorable for better gap width result. Energy range of 4 to 9 mJ seemed to provide minimum gap width on this occasion.

The reason why lesser energy still may not produce a very good gap width can be explained from the fact that at very lower energy, the sparks produced doesn't have enough intensity to remove the debris properly. As a result often the debris are not cleared from the gaps created and coagulate on the surface instead. This initiate consecutive sparks at the same area which cause over cut and gap width increase even though the spark energy is less. The reason for wider gap width at elevated energy level very logical. When the spark energy is high, it causes to produce deeper cavity on the surface. As a result the gap width value again increases.

Table 5.12: Fixed Parameters

Wire Speed	*Wire Tension*	T_{on}, T_{off} μs	*Wire Dia* μm	*EDM Speed* μ/s	*Short*	*Open*
30%	40%	9, 12	70	10	5	5

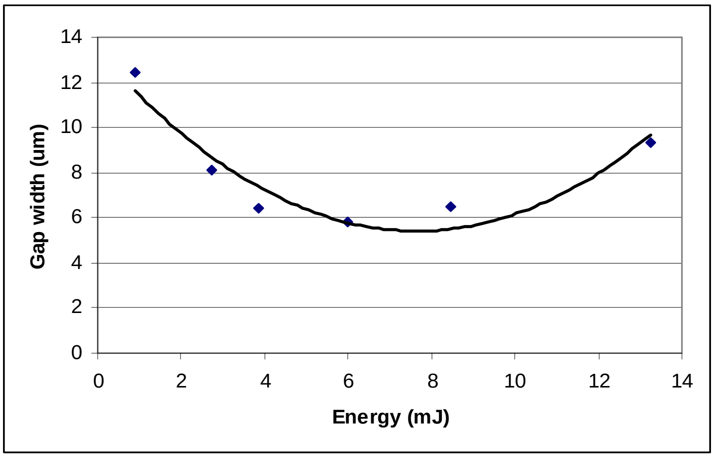


Figure 5.12: Effect of Energy on gap width

5.3.4 Effect on Surface Roughness

Surface finish or surface roughness is often an important parameter which is generally influence by the current on time and peak current. The effect of current on the surface roughness is demonstrated in the figure 5.13. It was observed that the surface roughness value improved (decreased) with increasing resistance, therefore with decreasing current. The results demonstrated that with increasing energy the surface condition deteriorate and the Ra value increase. This is very reasonable because higher energy cause deep crater on the surface. It was noted that for 70µm wire diameter, it broke with the lowest resistance setting. Thus only other 3 values of current from 3 other resistances were considered.

Table 5.13: Fixed Parameters

Wire Speed	*Wire Tension*	*T_{on}, T_{off} µs*	*Wire Dia µm*	*EDM Speed µ/s*	*Voltage volt*	*Short*	*Open*
40%	40%	30, 30	70	10	80	10	5

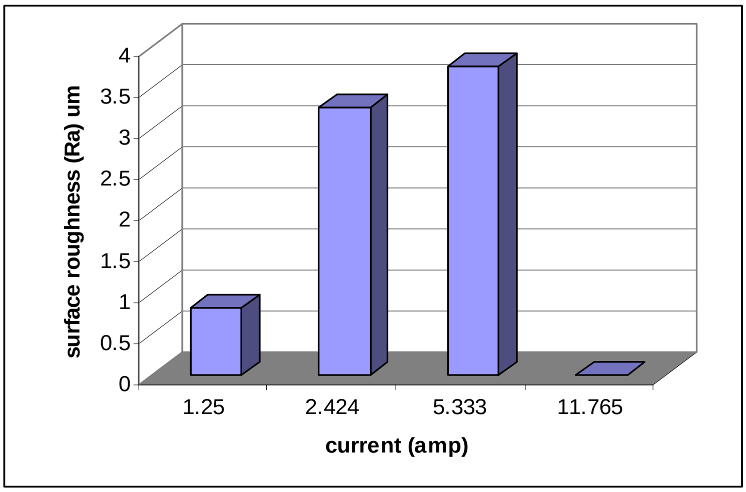


Figure 5.13: Effect of current on surface roughness

5.4 EFFECT OF SPARK ON AND OFF TIME

The WEDM machine creates spark discharge by using a pulse generator and the frequency of the spark discharges is dependant on the T_{on}/T_{off} value. The spark on time and off time are very important in determining machining characteristics such as gap width, material removal rate and surface roughness.

5.4.1 Effect of Spark on time (T_{on}) on machining time

The effect of spark on time on the machining time at elevated temperature is studied in the following experimental findings. At elevated voltage (150 volt), the effect of T_{on} machining time is very unusual. Generally high T_{on} means more machining energy, so it is expected that increasing T_{on} will have faster machining rate. But in this graph it is seen that with increasing T_{on}, the machining time keep increasing. So, not necessarily T_{on} improves machining time. At higher voltage such as 150 volt, the optimum value of T_{on} most tentatively lies near or below 8.

The reason behind this trend is most probably because of:

- More short-circuit with increasing T_{on} which causes the electrode to retract more frequently. This process contributes to higher machining time.

Table 5.14: Fixed Parameters

Voltage Volt	*Res. Ω*	*T_{off} μs*	*Wire Speed /Tension*	*EDM Speed μm/s*	*Short*	*Open*
150	33	36	50%, 25%	10	10	20

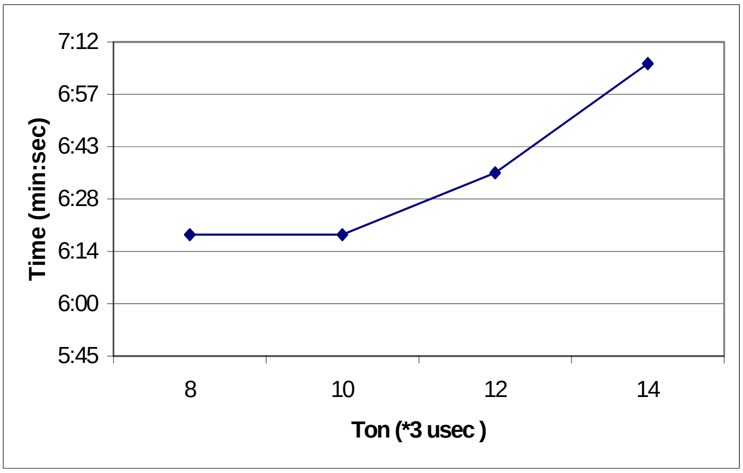


Figure 5.14: Effect of spark on time on machining time

Additional experiments were conducted to study the effect of spark on time. The data and experimental results are given below:

As it was observed from figure 5.15 that machining time decrease with increase with T_{on} up to certain limit. After which even increasing T_{on} doesn't have considerable impact on machining time.

Table 5.15: Fixed Parameters

Voltage Volt	*Res. Ω*	*T_{off} μs*	*Wire Speed /Tension*	*EDM Speed μm/s*	*Short*	*Open*
150	33	36	50%, 25%	10	10	20

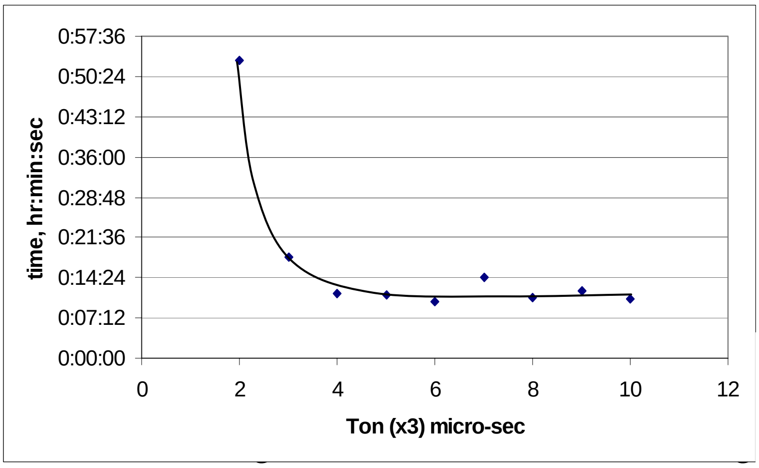


Figure 5.15 Effect of spark on time on machining time

The reason behind it is because when T_{on} was increased the spark remained on for longer time. Seemingly it may help to remove the material faster, but with increasing T_{on} there is more chance for short circuit. As a result of this the electrode retracts more from the surface and that slows down the machining.

This is the reason why increasing T_{on} doesn't continue to produce lesser machining time as one might expect. Comparing to the experimental result of graph A it can be concluded that when T_{on} increase after certain value at the elevated voltage the effect is quite negative. In this case T_{on} value over 10 (time 3 micron sec) yields such negative effect such as increasing machining time with increasing spark on time.

In picture 4.16 the machining time against duty factor is projected. Since the T_{off} was constant, the figure 5.15 and figure 5.16 shows similar pattern. The duty factor only shows significance when T_{on} and T_{off} are both changed at the same time. In this case it seems that a duty factor of 1 or near 1 gives the fastest machining time for this particular experiment.

Table 5.16: Fixed Parameters

Voltage Volt	*Res. Ω*	*T_{off} μs*	*Wire Speed /Tension*	*EDM Speed μm/s*	*Short*	*Open*
150	33	36	15%, 20%	10	10	20

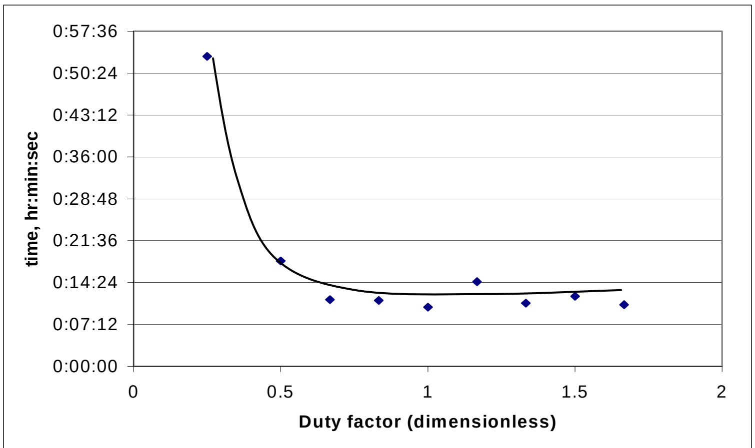


Figure 5.16: The effect of duty factor on machining time

Experiments of T_{on} on less spark energy were conducted. To obtain lesser spark energy higher resistance was selected. It was observed that when spark energy is less, smaller spark on time leads to very high and often non-feasible machining time. From this figure 5.17 it was again evident that increasing T_{on} doesn't always yield to better machining time. For 150 volt, here the best timing was obtained at 6 (*3 μs). Here only data with EDM speed = 5 μm/s are used.

Table 5.17: Fixed Parameters

Voltage Volt	*Res. Ω*	*T_{off} μs*	*Wire Speed /Tension*	*EDM Speed μm/s*	*Short*	*Open*
150	33	36	15%, 20%	10	10	20

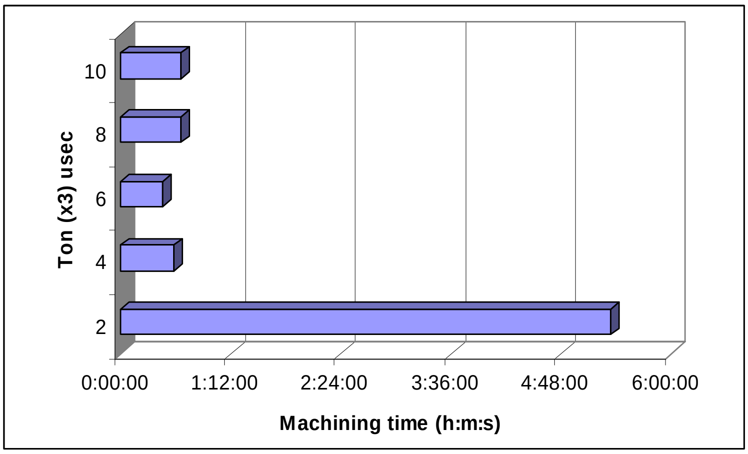


Figure 5.17: Machining time against spark on time

Next set of experiments were conducted at lower voltage and lower resistance. A voltage of 75 volt and 33 ohm resistance was selected. With T_{off} being constant (6*6 μs) the variation of machining time with T_{on} was demonstrated here. Only data that have T_{off}=6 have been used to construct this graph (excluding 1st reading as the time is too high which diminish the result of other values). From the figure 5.19 it was observed that machining time initially decrease up to a certain value but after that again increase. It is evident that the optimal value lies between the T_{on} values between 12 to 16.

Table 5.18: Fixed Parameters

Voltage Volt	*Res. Ω*	*T_{off} μs*	*Wire Speed /Tension*	*EDM Speed μm/s*	*Short*	*Open*
75	33	36	15%, 20%	10	16	8

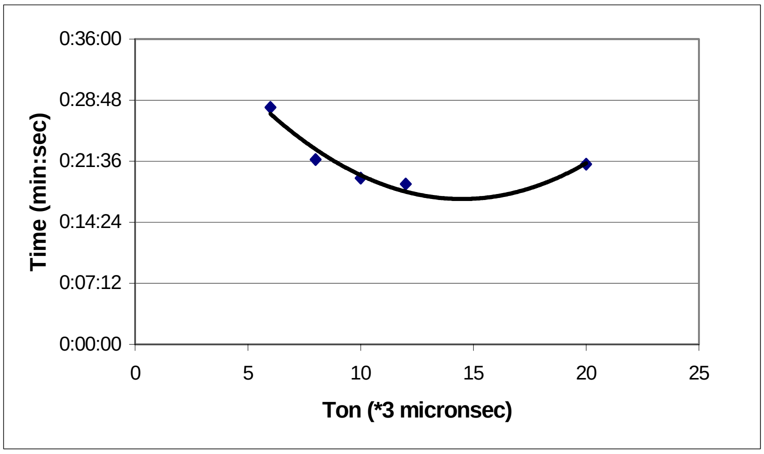


Figure 5.18: Effect of T_{on} against machining time

In the next set of experiments higher range of spark on time was used. Experiments were conducted up to 105 micron second spark on time. At lower energy level with parameter set at 75 volt and 33 ohm revealed that the effect of T_{on} on time is varying. From figure 5.18 it seems that particular values of T_{on} gives better machining time than the rest. T_{on} values both below and above the range of 15(x3) to 25(x3) worsens the machining time. Thus for other parameters remain unchanged the optimal value for T_{on} can be roughly considered at 25(x3) since it is the best timing we got from the experiment.

Table 5.19: Fixed Parameters

Voltage Volt	*Res. Ω*	*T_{off} μs*	*Wire Speed /Tension*	*EDM Speed μm/s*	*Short*	*Open*
75	33	36	15%, 20%	20	16	8

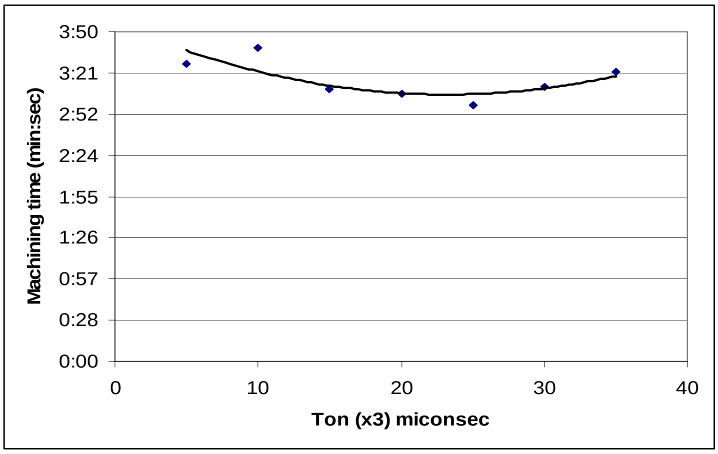


Figure 5.19: Effect of spark on time on machining time at 75 volt

In the following experiment lower range values of spark on was used to observe the machining time. It was seen that optimum machining time was obtained for Ton value of 8(x3) to 12(x3) micron seconds.

Table 5.20: Fixed Parameters

Voltage Volt	*Res. Ω*	*T_{off} μs*	*Wire Speed/Tension*	*EDM Speed μm/s*	*Short*	*Open*
75	33	36	15%, 20%	20	16	8

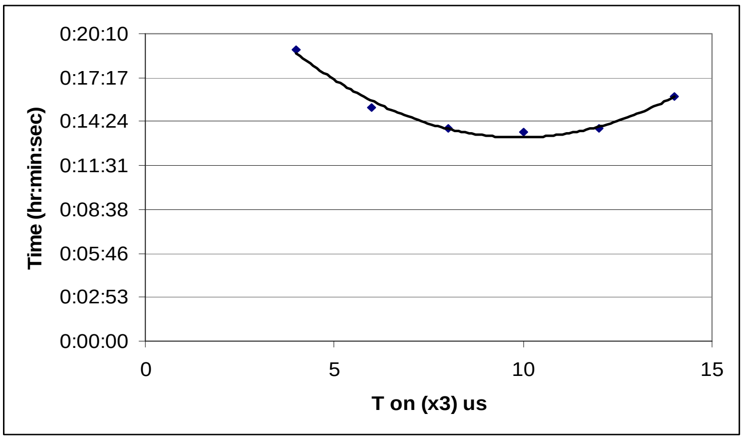


Figure 5.20: Effect of T_{on} against machining time.

5.4.2 Material Removal Rate

The effect of spark on time on the material removal rate was studied. The experimental data plotted on the graph showed a pattern where at lower spark on time the MRR was low, then increased for some particular range and then again decreased. It was found that for a range between 20 to 30 the material removal rate was higher.

Table 5.21: Fixed Parameters

Wire Speed	*Wire Tension*	*Voltage volt*	*Res. Ω*	*EDM Speed μm/s*	*Short*	*Open*
30%	35%	95	33	20	10	5

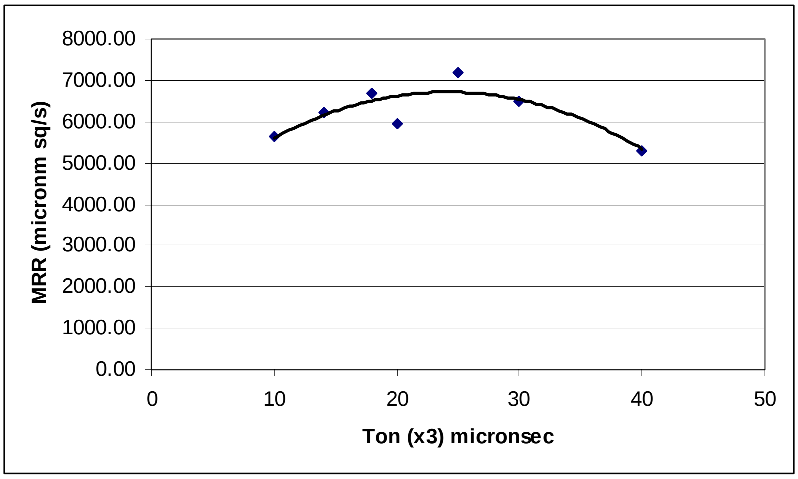


Figure 5.21: Effect of spark on time on material removal rate

5.4.3 The Problem with Duty Cycle

The same data from was plotted for machining time against duty cycle in figure 5.22. The points are quite chaotic and not revealing any pattern. This is because duty cycle is not a true representative of machining condition. The T_{on} and T_{off} can be with very different set of values even at the same duty cycle value. Although duty cycle is sometime used in the literature to demonstrate parameter effect, but in this case it is evident that it can be misleading.

Table 5.22: Fixed Parameters

Wire Speed	*Wire Tension*	*Voltage volt*	*Res. Ω*	*EDM μm/s*	*Short*	*Open*
30%	35%	95	33	20	10	5

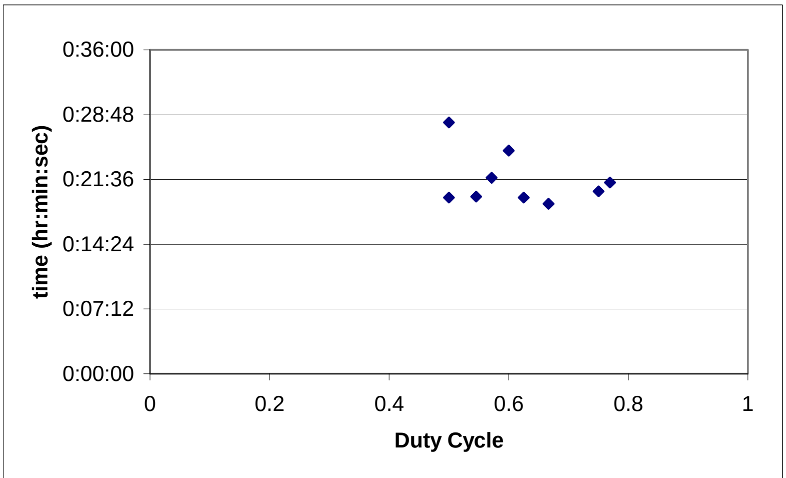


Figure 5.22: Duty cycle and its effect on machining time

5.4.4 Comparison of machining time with different set of parameter values

In order to observe the effect of Ton time on machining time, two set of parameter was used. In WEDM how the other parameters can affect the machining condition was realized from this experiment. Primarily the T_{on} and T_{off} was changed and the machining time was obtained. It was found that the best machining time was obtained between 20 to 30 T_{on} values. In both cases the machining time was higher in lower spark on time, which is reasonable because with low spark on time the energy imparted is quite low. In the middle range the timing is best.

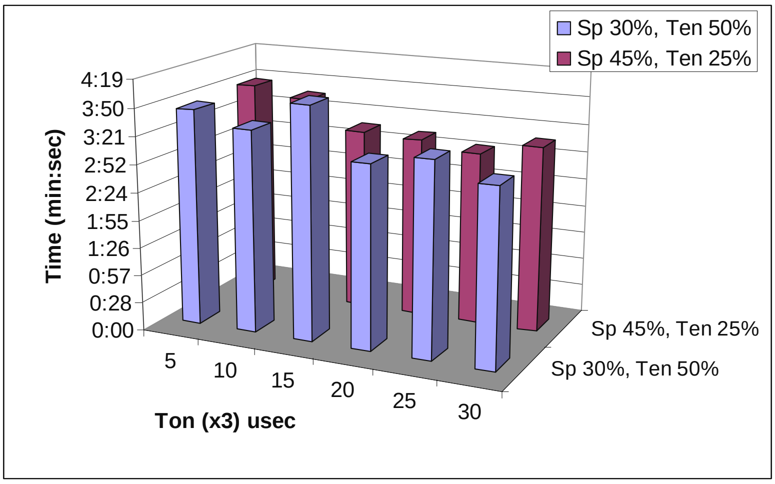


Figure 5.23: Effect of spark on time on machining time with different set of wire speed and tension

5.4.5 Effect of Spark on time (T_{on}) on gap width

The gap width is very much influenced by the spark on time. Thus the effect of spark on time was studied carefully.

In the following experiment spark on time from 15 to 105 micron second was selected and the corresponding gap width was measured. The plotted experimental value showed that the gap width increases in a linear trend. It was also demonstrated that minimum spark on time is more favorable for minimum gap width.

Table 5.23: Fixed Parameters

Wire Speed	*Wire Tension*	*Voltage volt*	*Res. Ω*	*EDM μm/s*	*Short*	*Open*
30%	35%	95	33	20	10	5

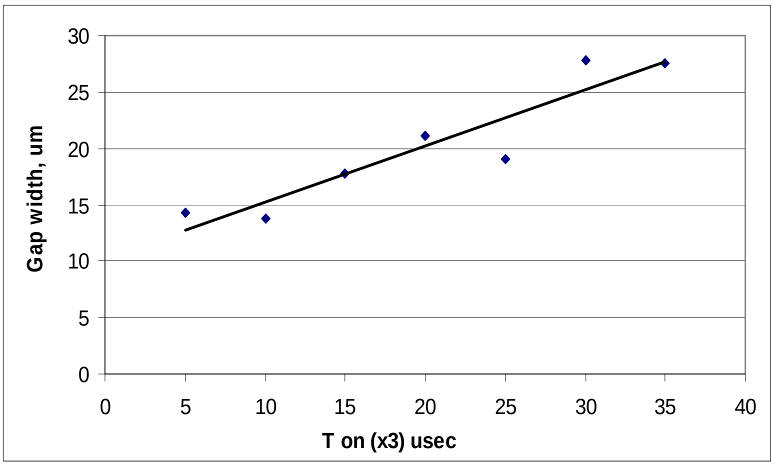


Figure 5.24: Effect of Spark on time on gap width

Another set of experimental results are presented in figure 5.25 for the study of gap width. The experiment was conducted at 75 volt and 33 ohm resistance. The results are average from successive experiments. As the spark on time is low, the discharge energy on the surface is low, which create very shallow craters. As a result the gap widths are less at lower value of spark on time. As the spark on time increase the gap width keep increasing. At the maximum value of 30 the gap width again reduces which is not really an indication of good gap width. At elevated spark on time the debris generated are very big in size and because of less time for the debris to clear, the removed part again coagulate back on the surface. This debris resoldified again on the wall of the machined slot produce the result of seemingly less gap width. In reality this is undesirable for the machining condition.

Table 5.24 Fixed Parameters

Wire Speed	*Wire Tension*	*Voltage volt*	*Res. Ω*	*EDM μm/s*	*Short*	*Open*
30%	50%	75	33	12	10	10

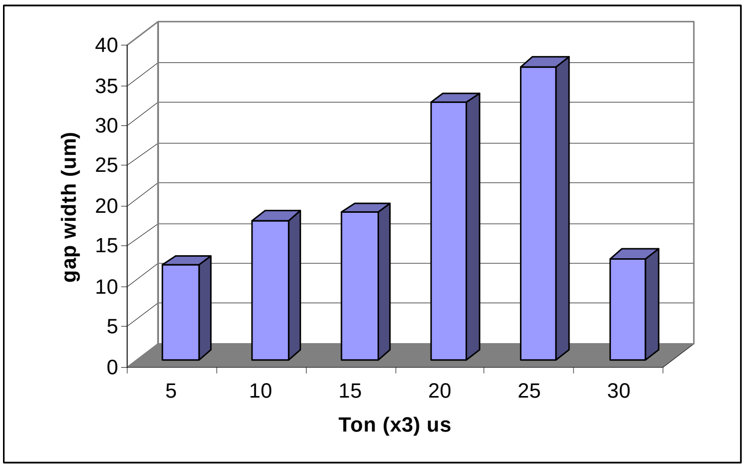


Figure 5.25: Effect of spark on time on gap width

Most of the experiments were conducted with a wire diameter of 70 micron. In the later part of the research wire diameter of 30 micron was also utilized (figure 5.26). The best gap width obtained was 7.23 micron at 30 micron sec spark on time. The trend of the gap width was linear and increasing with spark on time. This was the most consistent pattern for gap width against increasing spark on time.

Table 5.25: Fixed Parameters

Wire Speed	*Wire Tension*	*Voltage volt*	*Res. Ω*	*EDM µm/s*	*Short*	*Open*
30%	35%	90	100	5	10	5

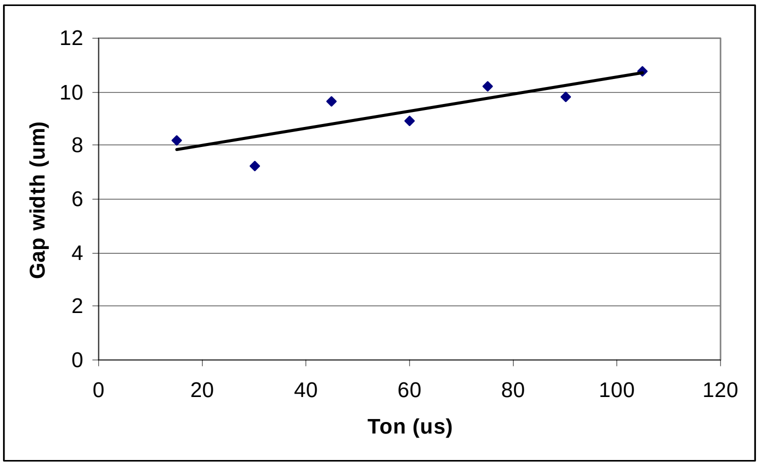


Figure 5.26: The effect of spark on time on gap width (wire diameter 30 micron)

5.4.6 The effect of T_{off}

The spark on time is attributed to the fact that it facilitates the recover of the dielectric after each spark on time, it allows time for the debris to be removed by the flowing dielectric fluid and also help stabilize the EDM condition.

The experimental data are plotted in figure 5.27. The trend of this graph is very interesting. Although it is intuitive that with a constant T_{on}, increasing T_{off} should increase the machining time. But here the result is quite opposite. With T_{off} increasing, the time to machine decreased. This peculiar trend can be attributed to that fact that giving enough time (with increased T_{off}, there are more opportunity) to solidify the debris and their removal. Thus better material removal condition is ensured.

Table 5.26: Fixed Parameters

Wire Speed	*Wire Tension*	*Voltage volt*	*Res. Ω*	*EDM μm/s*	*Short*	*Open*
50%	30%	75	33	12	10	10

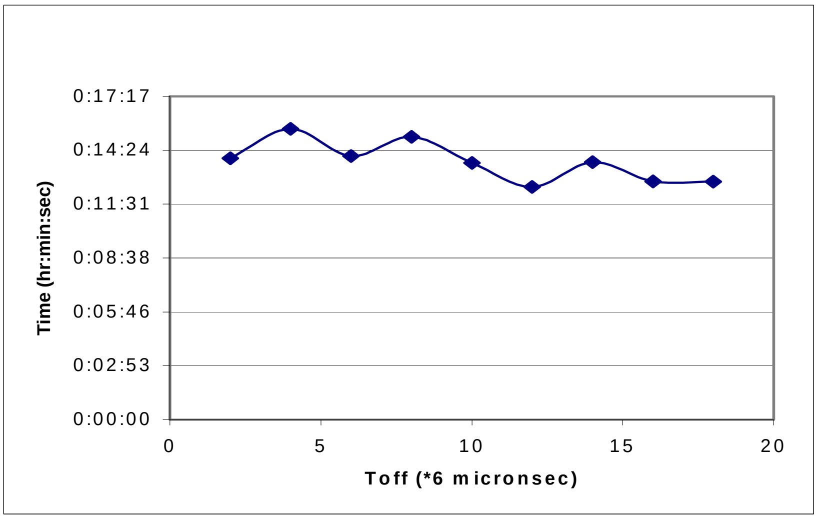


Figure 5.27: Effect of T_{off} on machining time

5.4.7 Effect of T_{on} and T_{off} on the gap width

In the following set of experiments spark on time and off time were varied successively. The data were plotted in the same graph (figure 5.28) to see the effect on gap width. Interestingly increasing both T_{on} and T_{off} value cause the gap width to increase as well. Also the machining time against T_{on} and T_{off} reveal that particular values in the middle range provide the best machining time. This range observed from 10 to 30 seems good for both T_{on} and T_{off}. But the variation in machining time was not so high, it fluctuated between certain time length such as 2 minute or even less. Thus it can be concluded that spark on or off time doesn't influence the machining time to great extent.

Table 5.27: Fixed Parameters

Wire Speed	*Wire Tension*	*Voltage volt*	*Res. Ω*	*EDM μm/s*	*Short*	*Open*
30%	35%	90	100	12	10	10

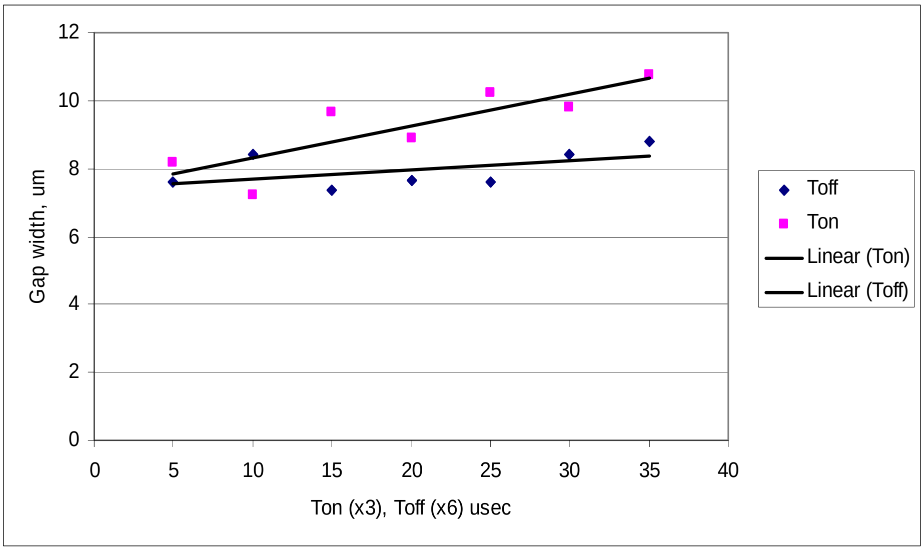


Figure 5.28: Effect of T_{on} and T_{off} on gapwidth

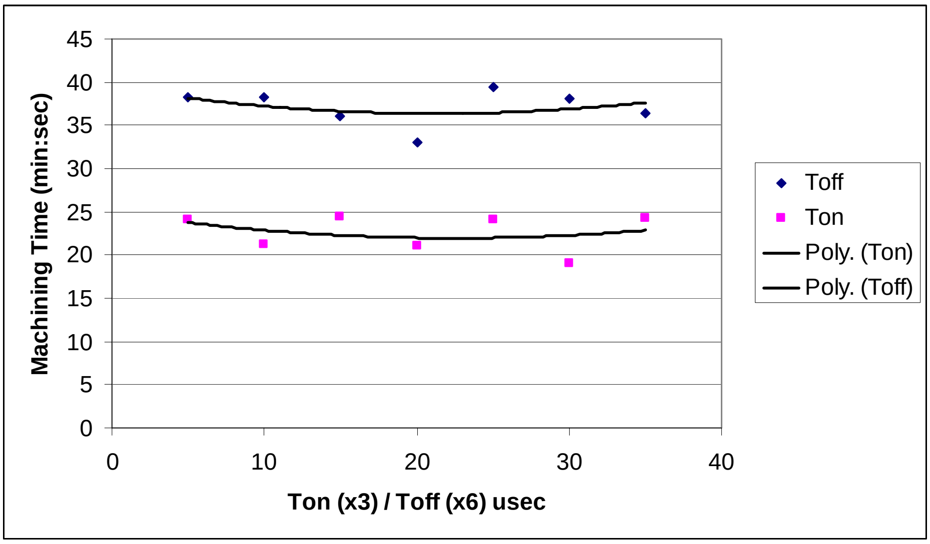


Figure 5.29: Effect of T_{on} and T_{off} on machining time

5.4.8 Influence of Spark on time on effective EDM speed

Although on the machine setting, the EDM speed is set at a particular value. But during machining, depending on the dynamic situation, the actual or effective EDM speed is different. From the 4.30 As we can observe from the above graph, although our machine setting EDM speed was 20 micron/sec, but for different values of T_{on}, the effective EDM speed varied. Since a T_{on} of 25 was found the best for machining time, it is the same optimal value for effective EDM speed. From the graph X it was clear that not necessarily a higher EDM speed ensure a higher cutting which also not much influenced by spark on time.

Machined path: A total of 2 mm in length (combining both horizontal and vertical direction) was cut.

Table 5.28: Fixed Parameters

Wire Speed	*Wire Tension*	*Voltage volt*	*Res. Ω*	*EDM μm/s*	*Short*	*Open*
30%	35%	75	33	20	10	10

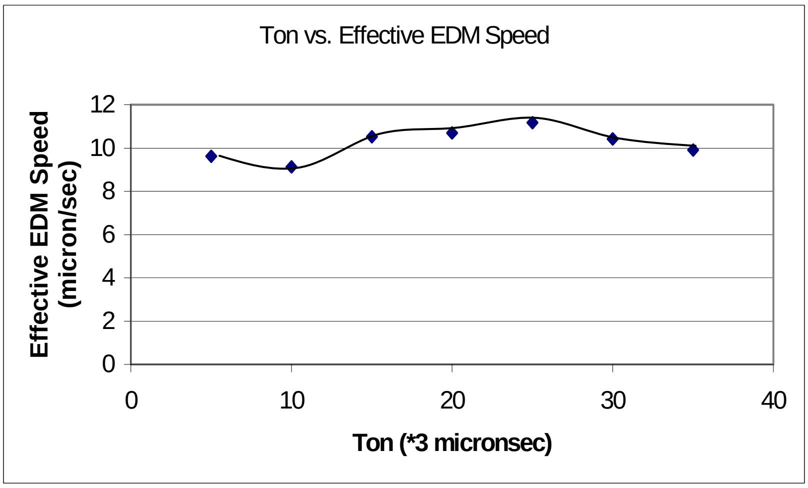


Figure 5.30: Effect of spark on time on effective EDM speed.

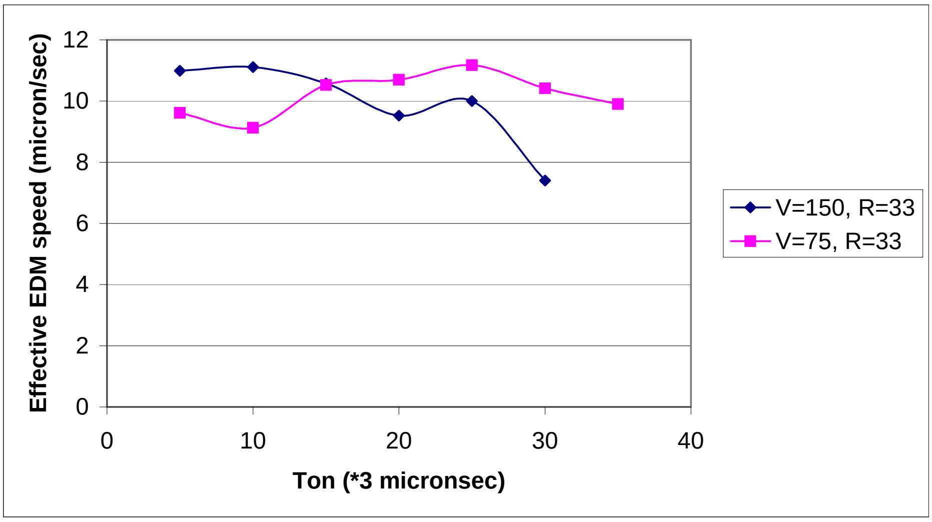
5.4.9 Comparison of Effective EDM speed at different Voltage setting

The effective EDM speed is an important concept to realize what the actual machining speed against different voltage setting is. Experiments were conducted for this purpose. For a lower current setting, (V=75 volt, I=2.272) the optimal effective EDM speed was found to be at a higher value of T_{on}, apparently at 25. But for a higher current setting, (V=150 volt, I=4.545) the optimal effective EDM speed was found to be at T_{on}=10.

The reason behind this different pattern could be because when current intensity is already high, a higher T_{on} only contribute to short circuit, thus disturbs the machining stability. Thus with higher T_{on} it takes more time to machine. For lower current intensity, the optimal machining time is at a moderately high T_{on}.

Table 5.29: Fixed Parameters

Wire Speed	*Wire Tension*	*Voltage volt*	*Res. Ω*	*EDM μm/s*	*Short*	*Open*
30%	35%	150 and 75	33	20	10	10



Graph 5.31: The higher the effective EDM speed, the better

5.5 STUDY OF EDM SPEED

5.5.1 On Machining time

The Wire EDM speed denoted by E, is a parameter used in the WEDM which is similar to the cutting feed rate of conventional machining. The feed rate controls the speed at which the wire approaches the workpiece, and in case of conventional machining this feed rate determines the cutting speed. However, in Wire EDM the machining speed is mainly dependent on the spark intensity and frequency, not the speed at which the wire approach towards 'the surface to be machined'. Even if a higher EDM speed is set, if there is not enough spark energy to erode the material, the wire will try to move forward and only touch the workpiece causing short circuit. No effective machining will occur. Thus selecting a proper value of E is very important.

If an EDM Speed, E set too low optimum cutting speed can not be achieved and machining will take much longer time. Again too high E speed will again only create unfavorable machining condition by frequent short circuiting, causing delay.

Thus series of experiments were conducted to find optimum EDM speed. From the study of EDM speed against time it was found that with higher EDM speed the machining time reduces, but this is not true to the whole range. The experiments were performed from a range of 2 μm/s upto 60 μm/s. It was found from the experimental data when plotted in graph that between 12 to 30 μm/s EDM speed provided the best result in terms of machining speed.

Initially when the EDM speed was too low, such as 2 to 10, the machining time was quite long. Suddenly at the value of 12 there is a sudden jump and reduction in the machining. It could be because depending on other factors such as spark on/off time, spark energy, wire diameter etc. there is a optimum combination near the value of 12 μm/s where there seems to be a well reduction of machining time. Again toward the other end of EDM speed such as 40 and 60 μm/s, machining time again seems to increase. This is because for particular energy intensity, if the EDM speed is too high that only creates undesirable machining conditions such as frequent short circuit which seems to the case here. When the short circuiting is frequent, obviously the wire is retracted more and thus machining time again increase.

Two set of experiments were performed, such as for low voltage and after high voltage. For low voltage, since the energy is less intensive than higher voltage; it seems the effect of EDM speed is more clearly understood. But when more energy is applied by selecting a higher voltage (such as 150 volt) the machining time is very much influenced by the energy alone. Thus the subtle effect of EDM speed is overtaken, and thus at higher speed more EDM speed gives faster machining time. Since the energy intensity is already high, more material is easily removed and a higher EDM speed aids machining speed.

Table 5.30: Fixed Parameters

Wire Speed	*Wire Tension*	T_{on}, T_{off} μs	*Res.* Ω	*Voltage Volt*	*Short*	*Open*
20%	15%	24, 36	33	75	10	10

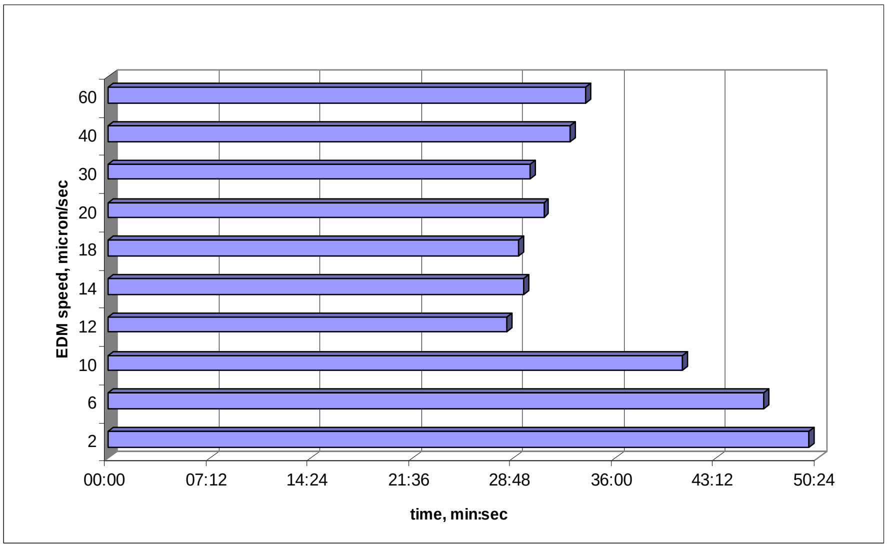


Figure 5.32: Effect of EDM speed on machining time at lower voltage

Table 5.31: Fixed Parameters

Wire Speed	*Wire Tension*	T_{on}, T_{off} μs	*Res.* Ω	*Voltage Volt*	*Short*	*Open*
20%	15%	24, 36	33	150	10	10

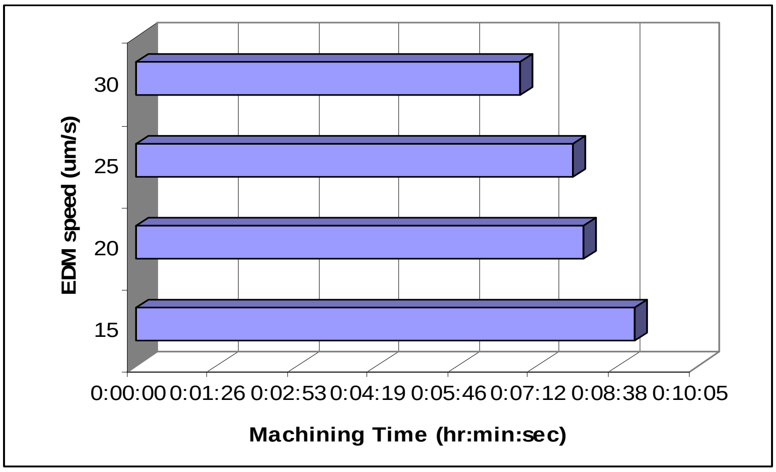


Figure 5.33: Effect of EDM speed on machining time at higher voltage

5.5.2 On Gap width

The experimental result of gap width against EDM speed is shown in figure 5.32. It is apparent that with increasing the EDM speed, the gap width also increases. Generally the EDM is not supposed to affect the gap width since EDM speed only signifies the motion of the wire. Yet such values obtained from repeated experiments can be explained by the fact that when EDM speed is higher, there is persistent short circuiting. Every time there is a short circuit, the wire electrode retracts and again after some delay proceeds with machining. Because of such repeated operation, at high EDM speed, more machining is performed on the same area which leads to more material removal. As a result the gap width becomes larger at higher EDM speed. It seems from the graph that the lower values should be selected to obtain a lower and better gap width.

Table 5.32: Fixed Parameters

Wire Speed	*Wire Tension*	T_{on}, T_{off} μs	*Res.* Ω	*Voltage Volt*	*Short*	*Open*
30%	30%	18, 36	33	150	10	30

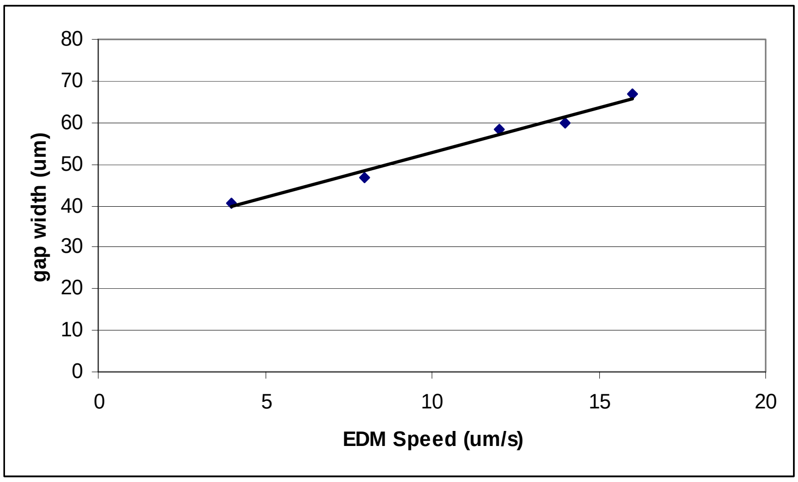


Figure 5.34: EDM speed vs. gap width

5.5.3 Finding Effective EDM Speed

EDM speed is the speed of the advancement of the wire during machining. Although EDM speed is suppose to determine the speed of the electrode advancement, the actual EDM speed is different than the set EDM Speed. This is because when EDM is in operation, because of the nature of spark the electrode may need to hold in the position or retract or move forward. Based on the parameter settings thus even though the EDM speed is set to some particular value, during machining it can not be exactly followed. Thus experimental data was collected and later from calculation the effective speed was found.

The effective EDM speed gives an indication about the actual speed that is being obtained during the machining. Effective EDM speed is measured by dividing the actual machined distance by the amount of machining time spent and is expressed by μm/s unit. From such knowledge too high or too low setting of EDM speed can be avoided and thus machining time can be saved. For example from the experiments it was found that in case of 150 volt, EDM speed between 4 to 16 μm/s yielded effective EDM Speed in the range of 1.023 to 1.86 μm/s only. So in this case it would not be advisable to set an EDM speed too high because that will only create additional short circuits.

It is again evident that a higher set EDM speed may very well yield low effective EDM speed. For example here EDM speed as high as 60 μm/s yielded an effective EDM speed of 1.52 μm/s only. From the plot it was observed that effective EDM speed was optimum between a range of 25 to 40 μm/s. At low EDM and at high EDM speed set at the machine, in both cases the effective speed was low compared to the middle range.

Table 5.33: Fixed Parameters

Wire Speed	*Wire Tension*	*T_{on}, T_{off} μs*	*Res. Ω*	*Voltage Volt*	*Short*	*Open*
30%	30%	18, 36	33	150	10	30

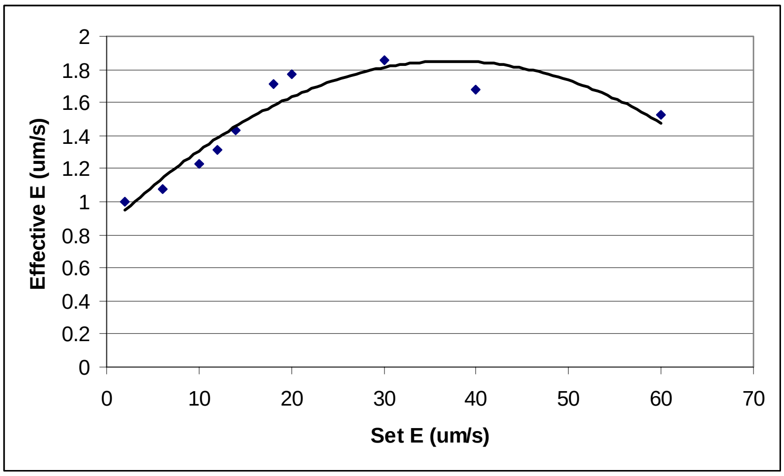


Figure 5.35: Set EDM speed vs. Effective EDM speed

5.6 STUDY OF WIRE SPEED

5.6.1 The effect of wire speed on machining characteristics

In the following experiment, the surface roughness was measured against the wire speed. It was found from the plotted experimental data that the roughness decrease with increasing wire speed. The reason behind these phenomena could be explained from the fact that higher wire speed facilitate:

1. Better stability of the wire electrode
2. More uniform removal of debris, thus preventing the debris to coagulate on back on the surface and causing rough surface roughness.

Table 5.34: Fixed Parameters

EDM Speed	*Wire Tension*	*T_{on}, T_{off} μs*	*Res. Ω*	*Voltage Volt*	*Short*	*Open*
20 μm/s	40%	30, 30	33	100	10	5

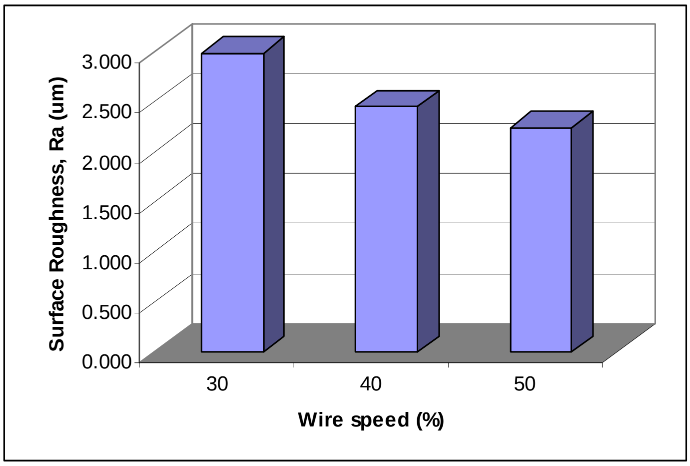


Figure 5.36: Effect of wire speed on surface roughness

5.7 STUDY OF WIRE TENSION

Wire tension indicates the amount of tension force exerted on the electrode wire. This tension force is imparted between the wire spool and the wire collector. The sensor circuit in the WEDM device controls the tension of the traveling wire. Generally increasing the tension is associated with the achievement of better surface finish due to the reduction in vibration.

The effects of tension on gap width and machining time are observed during the experiments. It was found that higher tension is favorable for both minimum gap width and faster machining time. The experimental graph obtained by plotting the gap width value against tension shows that gap width reduces with increasing wire tension and this trend is almost linear.

The machining time is also affected by wire tension. Machining time for both lower voltage (75 volt) and higher voltage (150 volt) was obtained at different tension values. For both voltages it was found that with increasing tension value the time decrease in a linear pattern.

Table 5.35: Fixed parameters: Low pressure, deionized water, St. Steel, 2 mm thick

Voltage Volt	*Wire Speed*	*T_{on}, T_{off} μs*	*Res. Ω*	*EDM Speed μ/s*	*Short*	*Open*
150	25%	15, 30	33	20	5	5

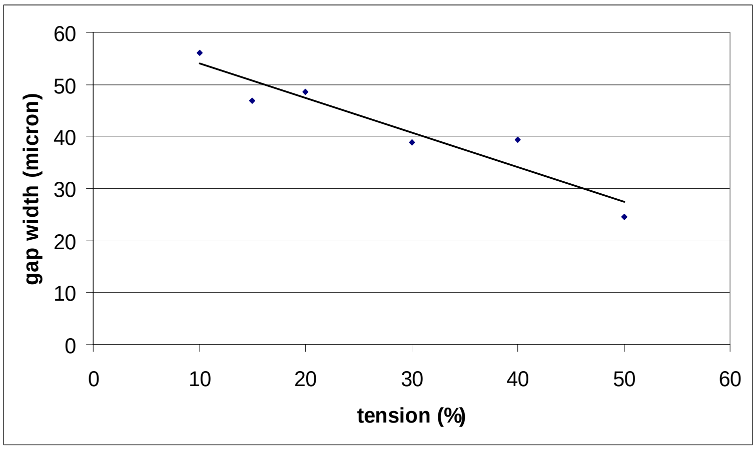


Figure 5.37: Effect of tension on gap width

Table 5.36: Fixed parameters

Voltage Volt	*Wire Speed*	*T_{on}, T_{off} μs*	*Res. Ω*	*EDM Speed*	*Short*	*Open*
75 and 150	25%	15, 30	33	20 μ/s	5	5

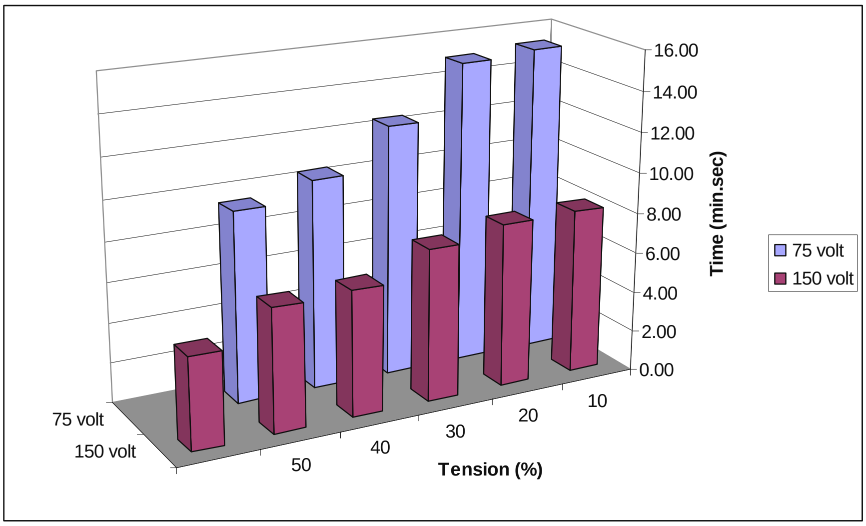


Figure 5.38: Effect of tension on time

5.8 THE COMBINED EFFECT OF WIRE SPEED AND DIELECTRIC FLUID

The dielectric fluid plays a vital role in WEDM. It is an integral element to the process. Dielectric fluid provides insulation against premature discharging, cools the machined area and flushes away the chips. During the experiments mostly deionized water and EDM oil was used as dielectric fluid. In the preliminary study the effect of deionized water as dielectric fluid and air (no dielectric fluid) was compared on machining characteristics. The results are studied at same wire run speed. For machining characteristics comparison, gap width and machining time was selected.

In figure 5.39 gap width values are observed at deionized water (dielectric flow) and air. It was found that at low wire run apparently speed better gap width was obtained for air. But at higher wire run speed, the gap width result doesn’t vary that much. But this apparent better gap width result doesn’t necessarily guarantee a better machining condition. Because at low magnification although the gap width seems low, but when observed more closely at SEM it was found that because of debris coagulated on the surface, the gap width seems less (figure 5.41). the huge amount of debris make the gap width look narrow, but in reality the actual machined gap width is much wider.

When deionized water is used, again at low wire speed the gap width reading gives smaller value than higher wire run speed. This phenomenon can also be attributed to the fact that debris deposited on the walls and debris did not remove properly. At higher wire speed the result for both dielectric flow and air is the same, so it can be concluded that air and deionized water doesn’t have much difference on the gap width.

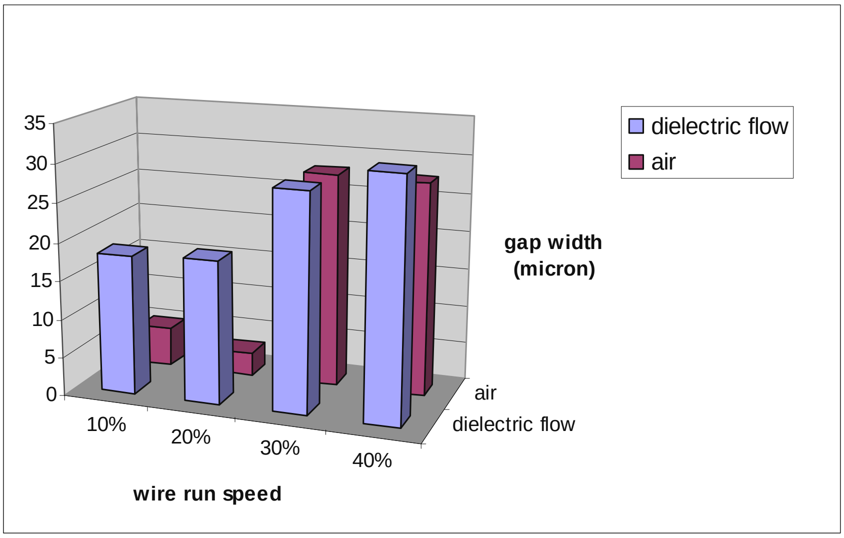


Figure 5.39: The effect of dielectric flow on gap width

The result of machining time for deionized water and air against different wire run speed is shown in figure 5.40. It is very much clear that machining time for deionized water is much superior to air. This is because, the sparking conditions are much better at deionized water. When no dielectric fluid is used, there are a lot of premature discharges which are not favorable to the machining. As a result the whole process is delayed and machining time increase when air is used. The wire run speed does not seem to have significant effect on machining time. For both deionized water and air the machining time doesn't vary much with wire run speed.

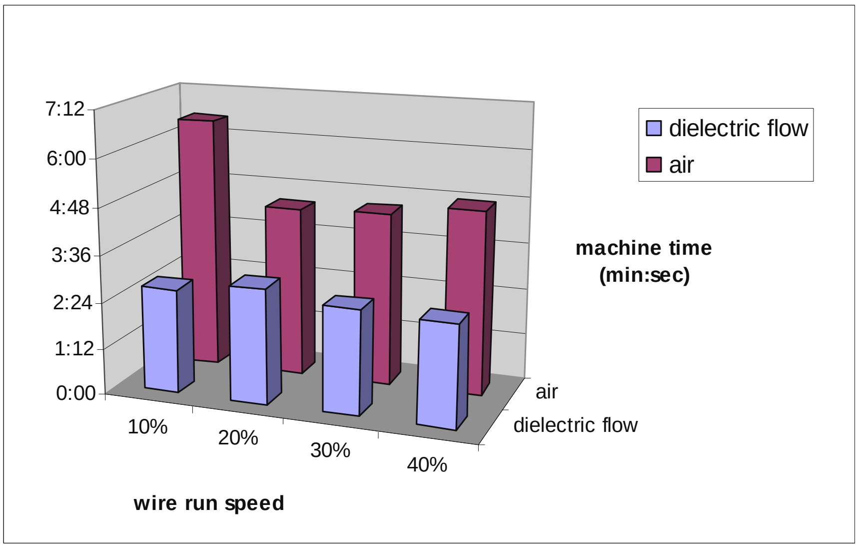


Figure 5.40: The effect of dielectric flow on machining time

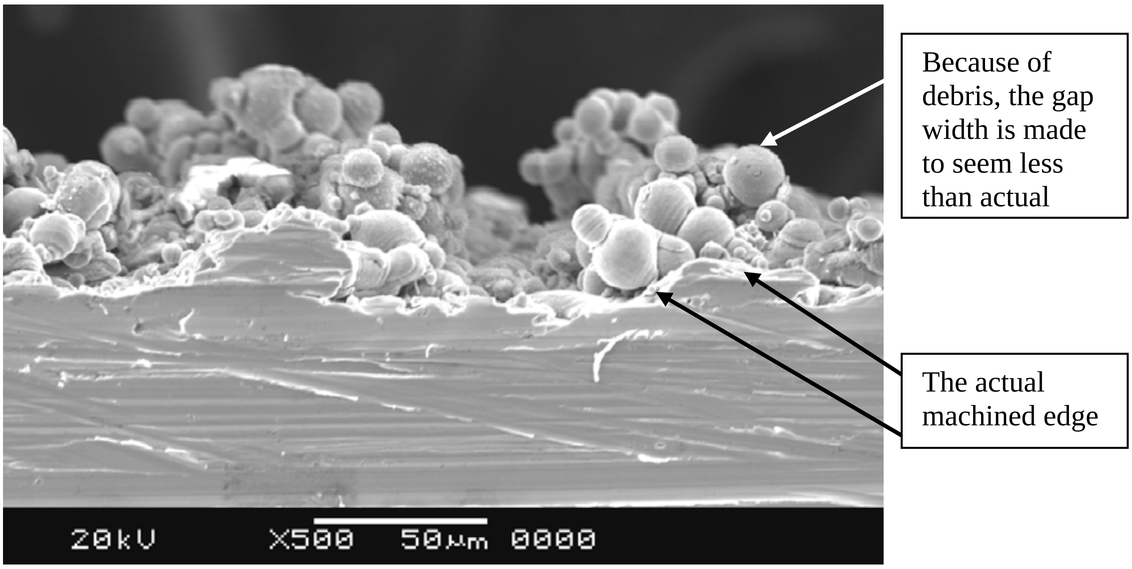


Figure 5.41: The coagulation of debris on the surface which sometime mislead the gap width reading

5.9 STUDY OF THE WIRE BREAKAGE PHENOMENA

The occurrence of wire rupture generally leads to a significant increase of machining time, a decrease of machining accuracy and the deterioration of machined surface. One of the most important problems in WEDM is related to wire breakage [Saha et. al, 2004]. From their finite element modeling Saha et. al. suggested that non-uniform heating is the most important variable affecting the temperature and thermal strains. Rajurkar and Wang [1991a, 1992] found that wire breakage is closely related to the sparking frequency. For μWEDM the problem is even more elevated since the wire used is below 100 micron (even down to 20 micron) in diameter as oppose to 250 micron in conventional WEDM.

Saha et. al (2004) mentions two main causes for wire electrode breakage:

1. High tension resulting from the complex work-piece geometry
2. When the thermal load and the impact of the electrical discharge not only adversely affect the wire tensile strength, but also erode the wire.

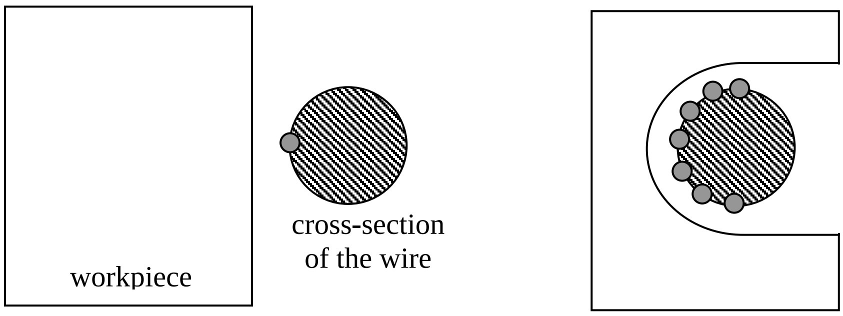


Figure 5.42: The distribution of the discharge changes depending on the position of the wire. When the wire is outside, the discharge point takes a line pattern. But once it is cut inside the workpiece it changes to a two-dimensional discharge pattern.

Thus the thermal load characterized by the temperature reached by the wire after the discharge along with the mechanical stresses of the wire material are the prime reason for wire breakage .When the wire is below 100 micron as in micro WEDM and the workpiece is of very thin as well, the wire breakage phenomena seems to be affected by other factors.

From the experiments conducted in this research, it was observed that when micro WEDM is done on much smaller level debris stuck inside the kerf is a major cause for wire breakage. This is called adhesion problem in the literature [Liao et. al., 1997].

The wire being smaller in diameter is another major factor for wire breakage. Some research [Watanabe et. al., 1990; Rajurkar et. al, 1991; Kinoshita et. al., 1982] related to wire rupture has been reported. The results show that the problem is largely associated with high density discharges being concentrated at some points on the wire. In some cases, 80-500 or more continuous discharges appeared at some concentrated points and wire breakage took place [Zhang et.al., 1992].

Since in WEDM the wire is negative, the amount of wear is quite high. From the observed wire diameter before and after experiment it was found that 28.5% for 30 micron wire diameter and 12% are contributed to the wear (figure 5.43 A, B, C, D).

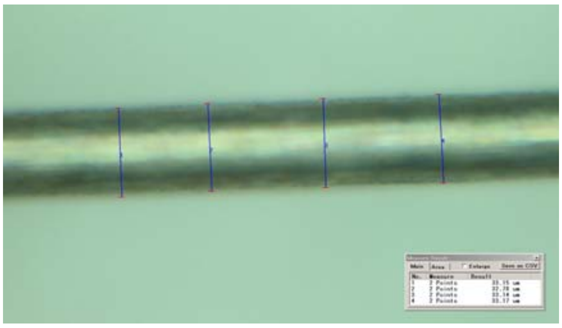


Fig 5.43 A: Fresh wire diameter (34 µm)

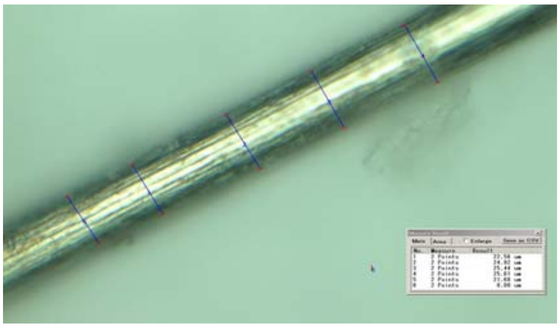
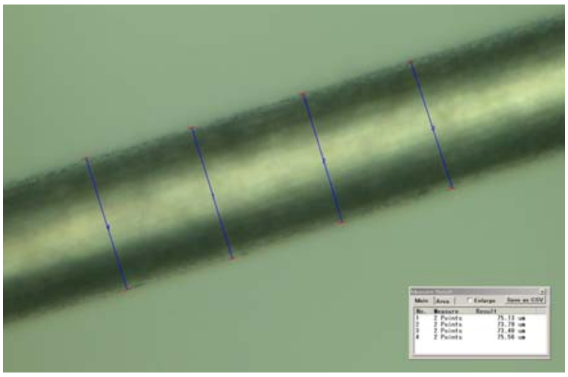


Fig 5.43 B: Used wire diameter (24.3 µm)



5.43 C: Fresh wire diameter (74 µm)

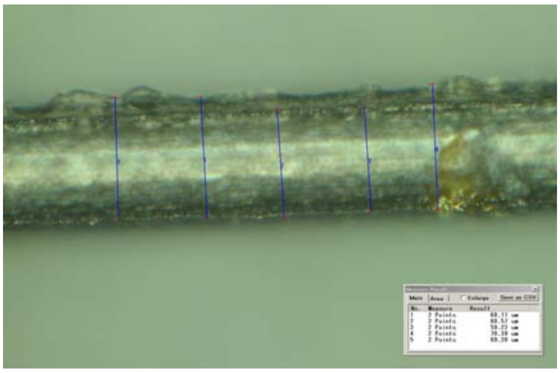


Fig 5.43 D: Used wire diameter (65 µm)

Figure 4.3: Wire diameter before and after machining

During the initial part of the research wear breakage was a very frequently encountered problem. To overcome the problem, the careful observation and selection of the WEDM parameter played a pivotal role.

Before a variable transformer was fitted to the WEDM machine, only two level of voltage could be used: 75 and 150 volt. Also there are 4 resistances which can be changed to impart different level of current or energy. The 4 resistances are 6.8 ohm, 15 ohm, 33 ohm and 100 ohm. Since the machining was done with 70, 50 and 30 micro diameter wire and on thin workpieces, the energy that is imparted, if too much then it causes the wire to break.

The WEDM parameter settings that were found to be non-favorable and promote wear breakage are: 150 volt with resistance below 33 ohm, such as 15 and 6.8 ohm. The amount of energy caused by such a combination such as 150 volt and 15 ohm (10 amp of current) and 150 volt and 6.8 (22.06 amp of current) – can not be sustained by wire below 100 micron and they immediately break.

Thus to avoid wire breakage a safe strategy would be to select voltage of 150 volt and resistance of 100 ohm. Even more safe is 75 volt and 100 ohm or 75 volt and 33 ohm. Choosing 75 volt will ensure better machining surface characteristics and very low possibility of wear breakage; but at the same time machining time will be very high.

Wire speed has some impact on wire breakage condition. If the workpiece is thicker (for micro WEDM using wire below 100 micron in diameter, even a 3 mm or greater thickness of workpiece may be considered thick), then there is greater risk that the wire will wear out soon due to successive sparks. In such scenario if the wire speed is increased fast enough so that the wire pass the machining area quite fast before it reach the breakage wear – then the wear breakage can be avoided significantly.

In the research it was found that for workpiece with thickness of 2 mm or less, wire speed of 30% (corresponding rpm value of 4.404) is enough to prevent wire breakage provided that the WEDM electrical parameters are set to acceptable level as indicated before. If the thickness of the workpiece is more than 3 mm then wire speed of 40% or more is recommended. For intricate shapes and cuts, too high wire speed can again cause wire breakage because of possibility that for very tiny fraction of time the wire may get caught inside the gap width and before it can release, may get broken. Apart from that a higher wire speed such as 35% to 45% can be selected without much problem except that fact that higher wire speed means higher wire consumption. A table with corresponding values of wire speed in % value and wire consumption rate is given in Appendix C.

Chapter 6

STUDY OF MACHINED SURFACES

6.1 INTRODUCTION

In this chapter critical study of the WEDMed surfaces were conduced. The effect on the surface integrity is discussed. Since the machined surface is an important result due to selecting WEDM parameters, thus the study is very important for identifying the best parameters.

6.2 SURFACE INTEGRITY

By the term ‘surface integrity’ the state or quality of the surface is generally meant. For micro level EDM or WEDM operation the important components that consist of surface integrity are:

1. Surface roughness
2. The nature of debris left on the surface
3. Machined edges
4. Heat affected zone

The effect of different parameters on surface roughness was studied in the previous chapter titled: Experimental Analysis.

While trying to have better surface roughness with accurate gap width, one component of surface integrity is often neglected – which is the nature of debris. In μWEDM, the proper removal of debris is very important. When very thin slots of less than 100 micron width are cut, the debris can not come out. And because of the failure of the micro debris to clear and coagulation of debris on the surface contribute to very poor surface.

For this reason the study to improve the nature of debris is important. And parameters that contribute to improve surface integrity because of debris are analyzed.

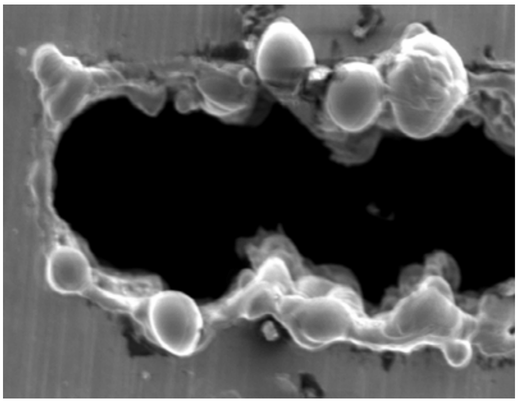


Figure 6.1: A

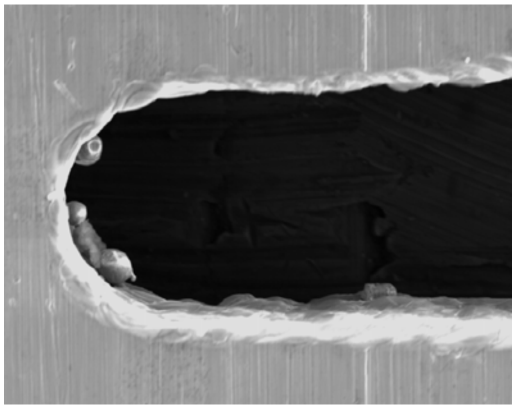


Figure 6.1: B

Figure 6.1: Figure A and B are an example of how the debris can affect machining. In figure A the debris are not cleared and thus coagulated on the surface during cutting the slow. Here the voltage was 75 volt and resistance 33 ohm. In figure B the condition of debris are very much improved when the energy was reduced by selecting a resistance of 100 ohm, while keeping the voltage same.

6.2.1 EDX Analysis

The two slots of figure 6.1 A and B were observed under EDX or Energy Dispersive X-ray analysis. EDX technique is used for identifying the elemental composition of the specimen, or an area of interest thereof. The EDX analysis system was an integrated feature of the scanning electron microscope (SEM).

The output of an EDX analysis is a plot of how frequently an X-ray is received for each energy level. An EDX spectrum normally displays peaks corresponding to the energy levels for which the most X-rays had been received. Each of these peaks is unique to an atom, and therefore corresponds to a single element. The higher a peak in a spectrum, the more concentrated the element is in the specimen.

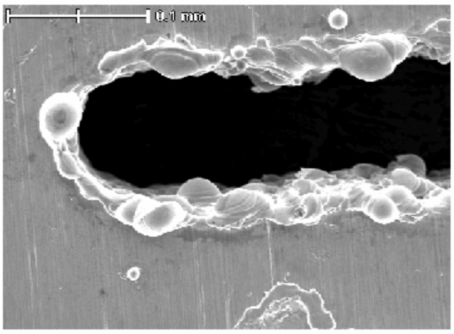
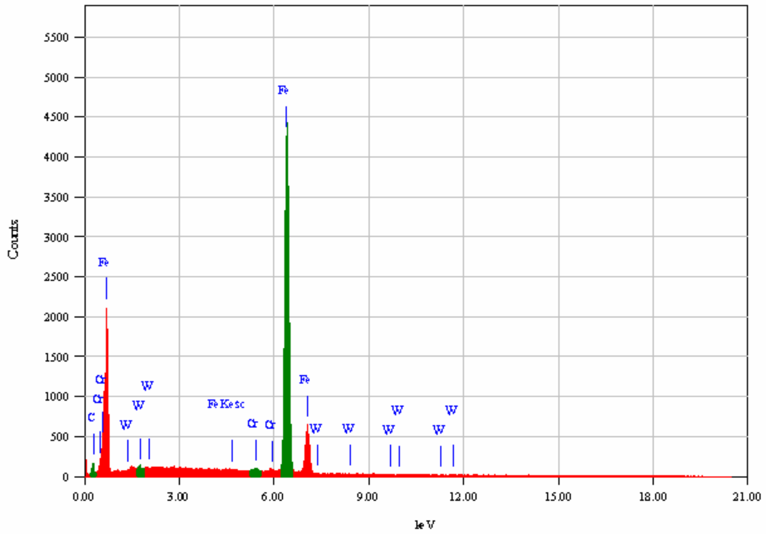


Figure 6.2: EDX analysis of the slot with a lot of debris coagulated on the surface. It was observed that the specimen contains traces of tungsten from the electrode. This is because during machining the electrode also wears out and some of the material from the electrode melts and migrate on the workpiece.



In the following figure 6.3 the EDX analysis of the slot in figure 6.1 B is presented. Compared to figure 6.1 A the condition of debris is much better here. Interestingly the EDX analysis shows that there are substantially lower traces of tungsten found. Since the workpiece was stainless steel, so in both cases Fe, Cr was there as constituent of stainless steel. Thus comparing between figure 6.2 and figure 6.3 it was clear that the debris not only contributes to poor surface condition but also by bringing in undesirable elements from the electrode, they can cause changes in properties of the machined part.

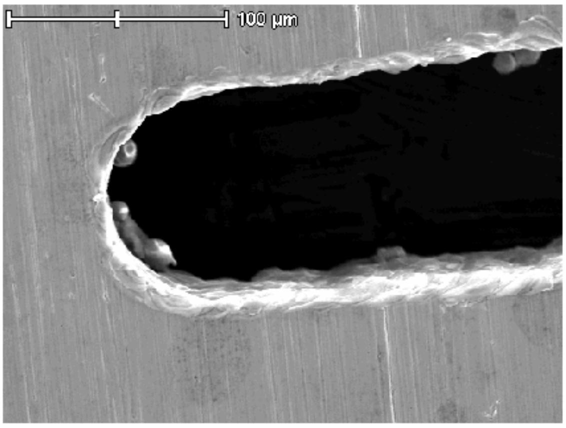
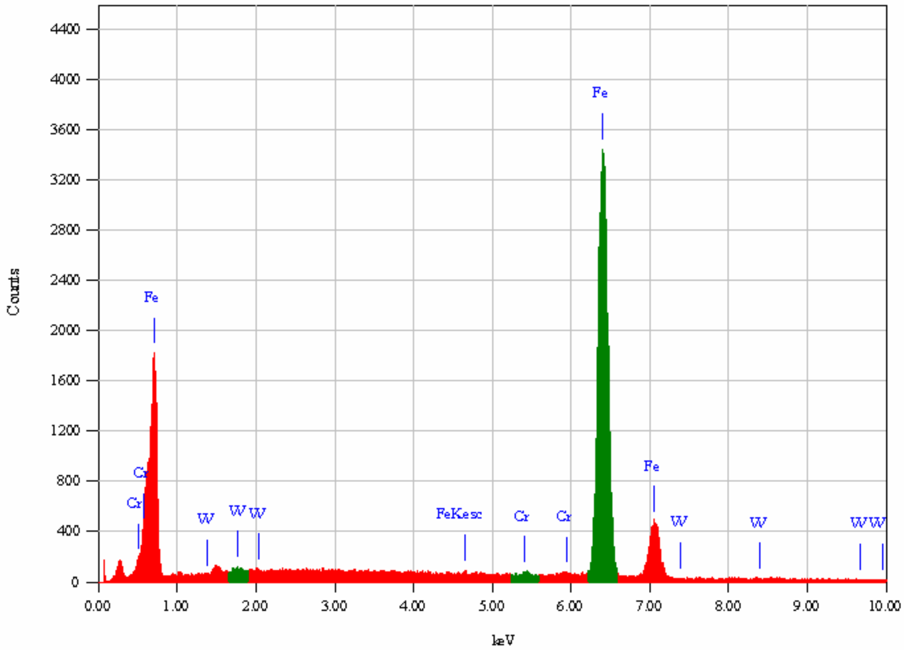


Figure 6.3: EDX analysis of the surface with better condition as regard to debris



In the following SEM figure the nature of the debris on the surface are demonstrated. Here the edge of the WEDMed workpiece is shown. Since the voltage intensity was high, so the particle of the molten materials re-solidified on the surface are quite large. Also, the cutting condition was non-immersed, without any flushing. Thus the debris were not properly removed as clear from the image.

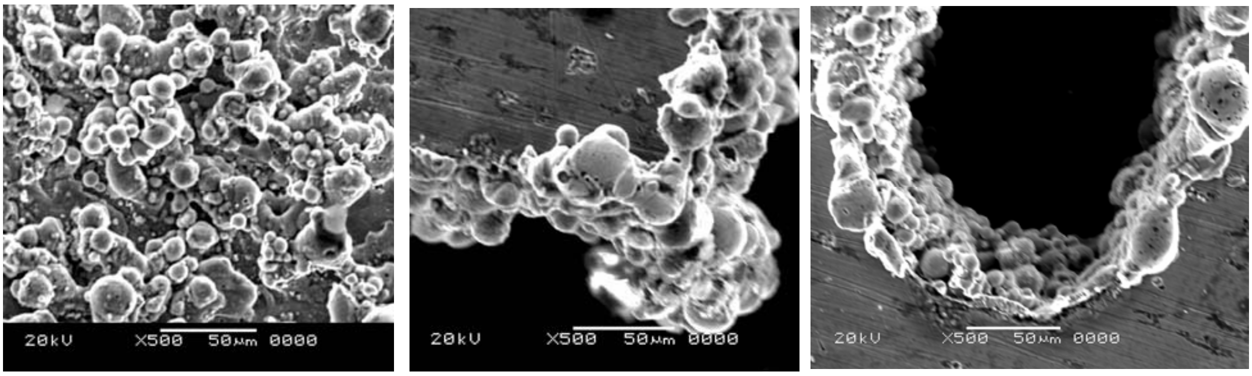
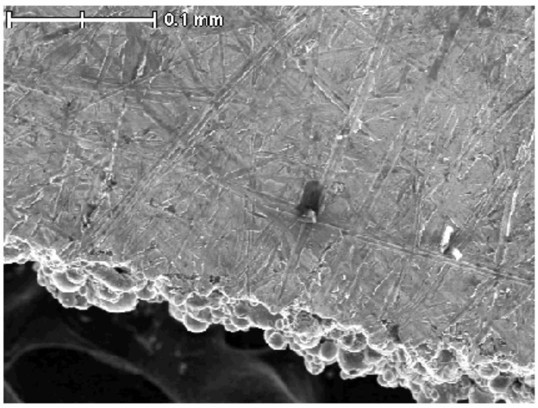


Figure 6.4: SEM close-up figures of EDM surfaces, surface edge and slot edge which were machined at elevated spark energy. Example of rough cutting. Parameters to cut: Material: Stainless Steel. 150 volt, 33 ohm, 4.545 amp, T_{on}= 24, T_{off} = 18, Short = 10, Open = 30, Wire speed 20%, Tension 25%

Another image of EDX analysis of the WEDM surface is given in figure 6.5. It was again demonstrated from the EDX image that the debris contain the electrode material, in this case tungsten (W).



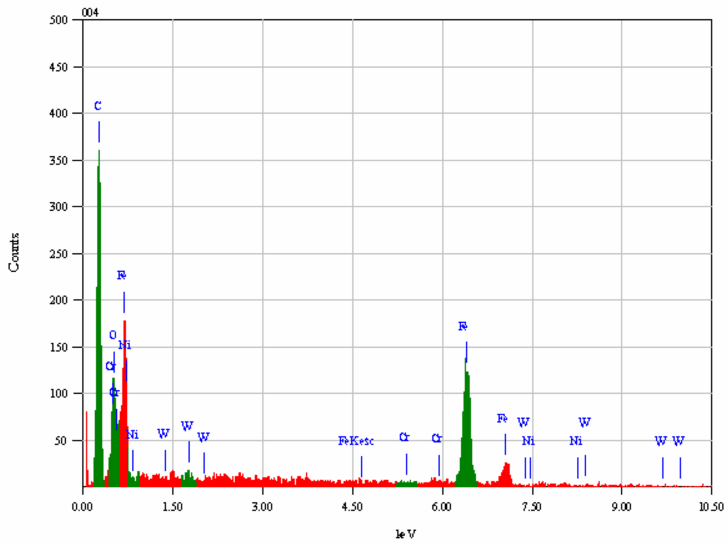


Figure 6.5: EDX image of WEDMed surface

6.3 OBSERVATION OF THE MACHINED SURFACE AT DIFFERENT VOLTAGE LEVEL

The WDEMed surface was observed after machining at different voltage level. The readings were taken by the Keyence Digital Microscope. The gap widths were measured digitally. From the captured images it was observed that with increasing voltage the edges became more jagged and rough. Thus the cut at lower voltage yielded better edge than the higher voltage. So from the observation, the lowest voltage should be selected.

Table 6.1: Fixed parameters

Wire Speed	*Wire Tension*	T_{on}, T_{off} μs	*Res.* Ω	*EDM Speed* μ/s	*Short*	*Open*
30%	40%	15, 30	100	5	5	5

Wire Diameter used was 70 micron. Material Stainless Steel.

Few of the example of voltage effect on the width of cut is shows in figure 6.6A to 6.6D.

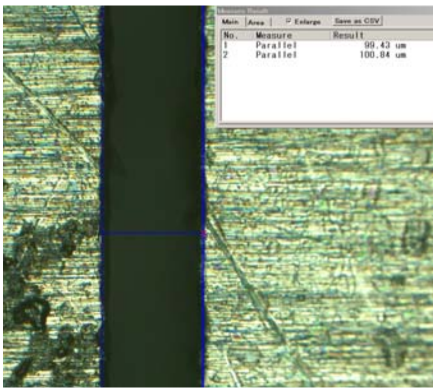


Figure 6.6 A: Voltage: 80 volt
Avg. Width of the cut: 100.76 μm

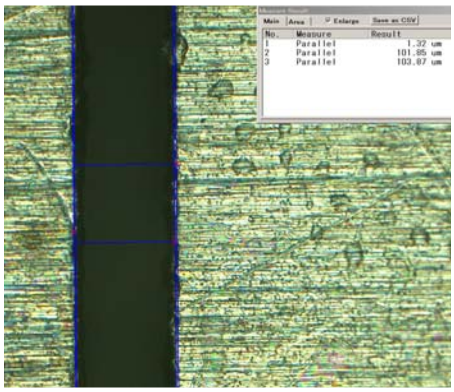


Figure 6.6 B: Voltage: 90 volt
Avg. Width of the cut: 102.2475 μm

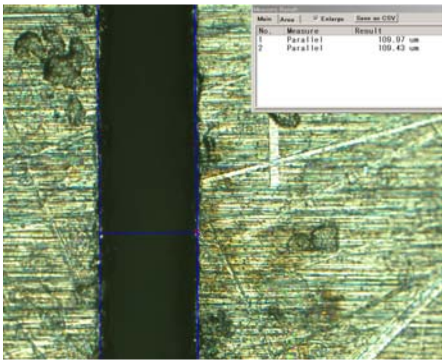


Figure 6.6 C: 130 volt
Avg. Width of the cut: 108.2975 μm

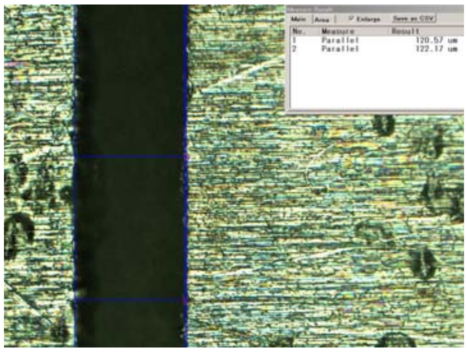


Figure 6.6 D: Voltage 150 volt
Avg. Width of the cut: 110.62 μm

6.4 OBSERVATION OF THE MACHINED SURFACE AT DIFFERENT TENSION

The machined surface was observed under the Keyence Digital Microscope. The surface profile was obtained and compared for different values of tension. As it was observed that the condition of surface profile improved gradually as the tension increased.

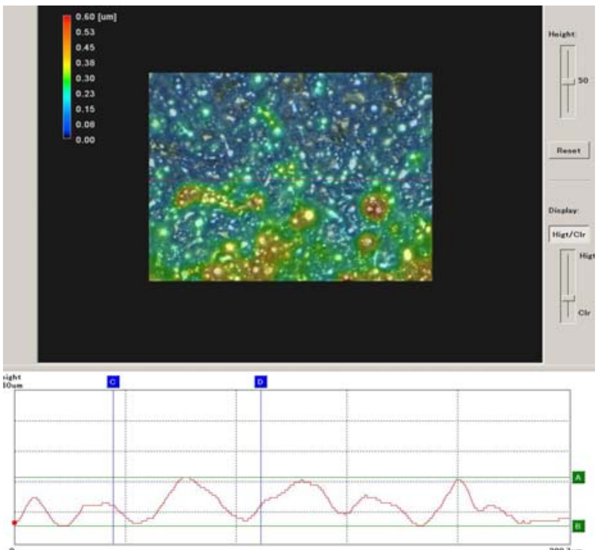


Figure 6.7 A

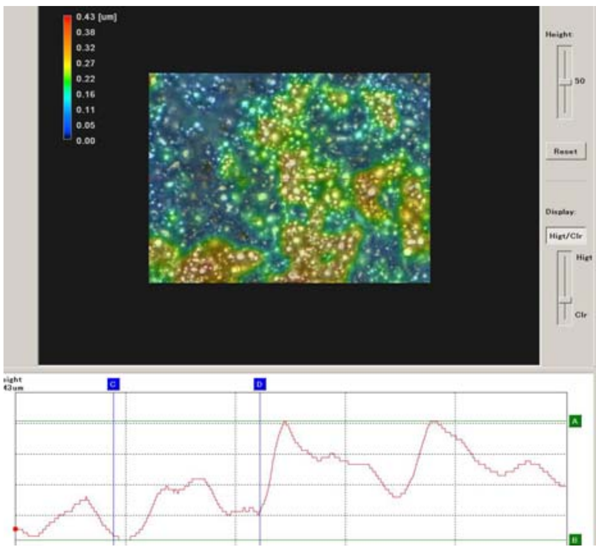


Figure 6.7 B

Figure 6.7: Example of surface profile measurement at tension of 30% and 40%. The average surface height was 0.3 μm and 0.215 μm respectively. Other fixed parameters used were: voltage 75 volt, resistance 33 ohm, T_{on} 18 μs and T_{off} 48 μs.

6.5 STUDY OF THE EFFECT OF WIRE TENSION ON WIDTH OF CUT

The wire tension on the width of cut was studied by cutting vertical and horizontal slot on the workpiece. For all the sections it is clear that there are some improvements in the cut width with increasing tension. The linear trend of the minimizing of the width of cut against the increasing tension is visible from the graph plotted in figure 6.9. This trend can be explained because of the fact that when wire tension increase, there is less wobbling of the wire and also less impact on the wire due to discharge.

Table 6.2: Parameters

Material: stainless steel, t=0.5mm	*Electrode: tungsten wire, d=0.07 mm*	*Wire speed:15%*	*EDM speed: 10 micron/sec*
Gap voltage=150 volt	R=33 ohm, I=4.545 amp	T_{on}=24 μs, T_{off}=36 μs	Short=10, Open=30

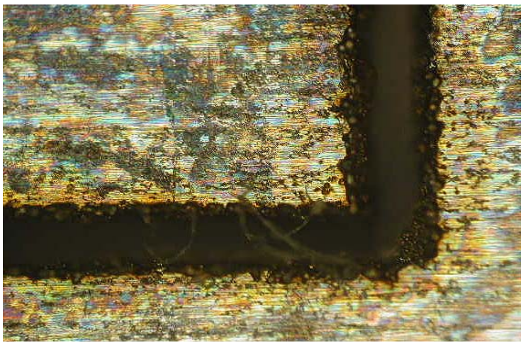


Figure 6.8 A: Tension 15%

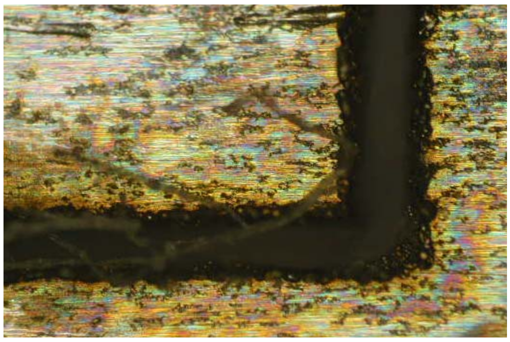


Figure 6.8 B: Tension 25%

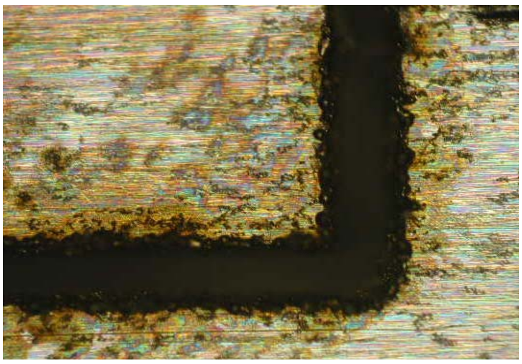


Figure 6.8 C: Tension 35%

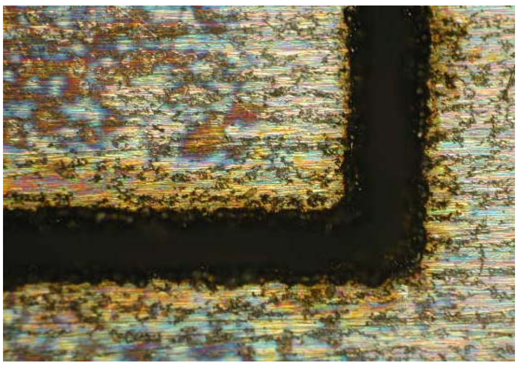


Figure 6.8 D: Tension 45%

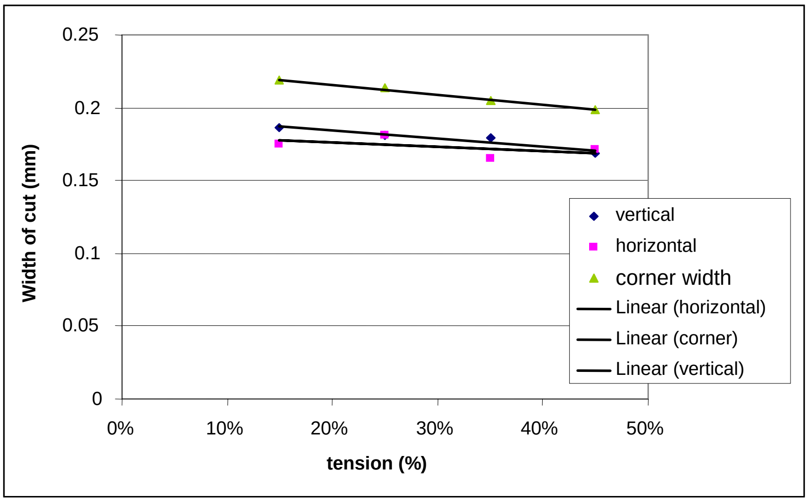


Figure 6.9: Width of cut with tension

6.6 OBSERVATION OF THE MACHINED SURFACE AT DIFFERENT SPARK ON TIME

The surface was observed under Keyence digital microscope at different level of T_{on} and T_{off} values. Figure 6.10 A and B was observed when T_{on} is 4 and T_{off} is 6. The surface profile presented in Keyence shows that the average surface height is about 0.245 micron meter. Figure 11 is another machining example at different spark on time.

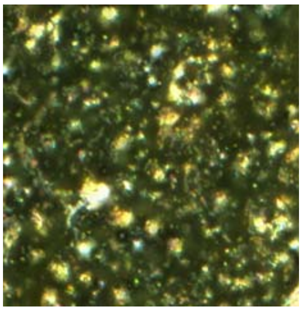


Figure 6.10 A: Photograph of the EDMed Surface Parameter value T_{on} =4, T_{off} =6 (mag. 1000X)

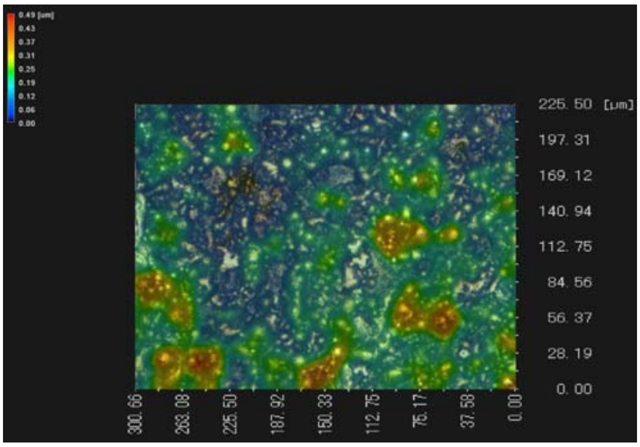


Figure 6.10 B: Surface profile at T_{on} of 12 and T_{off} of 36 μs.

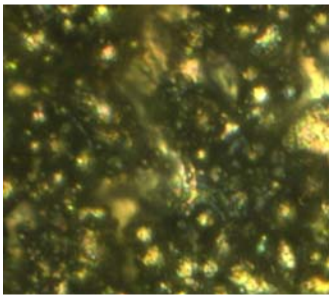


Figure 6.11 A: The closeup view of the WEDMed surface

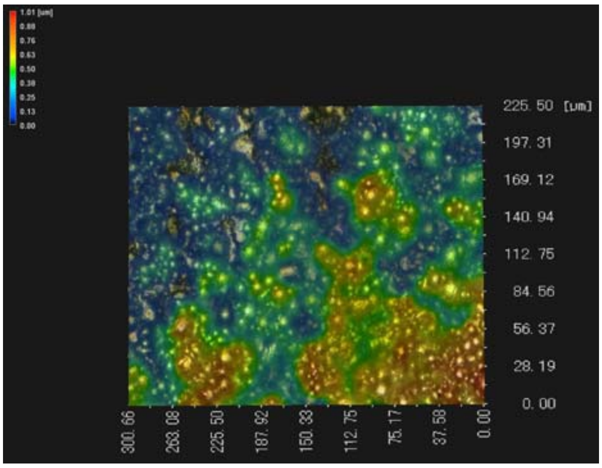


Figure 6.11 B: The surface profile of the surface machined at T_{on} = 30 and T_{off} = 36 µs The average surface height increased to 0.5005 micron which was due to the increased spark energy from the increased Ton time.

6.7 HEAT AFFECTED ZONE

In WEDM, the machining is done by converting electrical energy into thermal energy during the spark discharge. The thermal energy melts and vaporizes the workpiece material during the process. Because of the high heat generated, the molten work and electrode solidify on the work surface which creates a recast later and there is another zone created under the recast layer which is known as the heat affected zone (HAZ). The recast layer causes an uneven layer on the surface of the work piece, therefore affecting its dimensional accuracy. The HAZ is the area whereby the properties of the material decrease in strength and is more prone to fatigue failure and facilitates crack propagation. Therefore, the HAZ is an undesirable result of wire-EDM and experimental study is required to reduce it.

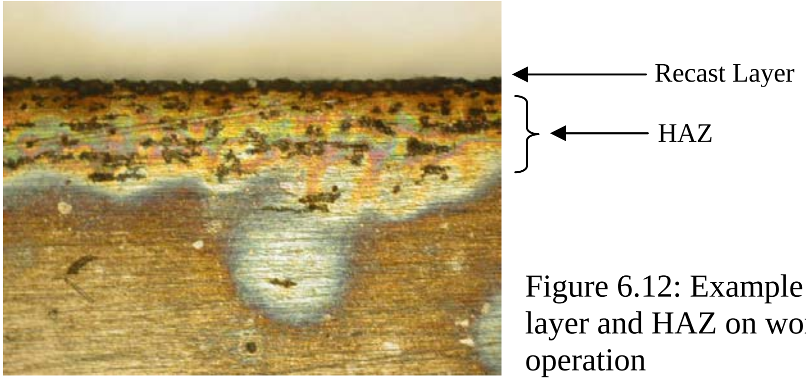


Figure 6.12: Example of buildup of recast layer and HAZ on workpiece after WEDM operation

6.7.1 Effect of dielectric on Heat Affected Zone

From experimental results it was found that dielectric plays an important role on the creation of HAZ. When machining was done in submerged dielectric, the extent of heat was reduced to greater extent as compared to low pressure flushing concentrating on smaller area.

As seen in figure 6.13 A and 6.13 B, the machined part on left was machined in submerged EDM oil whereas machined part on right is an example of machined surface in low pressure flushing. It is obvious that the HAZ is quite large in the second figure. As in low pressure flushing, the dielectric fluid is less compared to submerge machining, thus the amount of heat removed is much less.

Figure 6.13 A Figure 6.126 B

Figure 6.13: Photography of WEDMed surface showing heat affected zone

6.7.2 Effect of parameter on Heat Affected Zone

Although dielectric fluid have the major influence on the formation of HAZ, nevertheless the parameters are also important. The higher the spark energy, more heat is generated and the effect of heat penetrates more into the work material. Since in micro engineering, the workpiece dealt with are of smaller thickness and of less volume; thus application of very high energy result in deeper heat affected zone.

6.7.3 Guideline for minimizing Heat Affected Zone

Deeper heat affected zones are not desirable since they reduce the strength of the material which could lead to fatigue failure and facilitates crack propagation. The application of the machined workpiece may be negatively affected because of such phenomena.

Being a thermal machining process, there will always the inherent tendency of the creation of HAZ in WEDM. This can not be completely eliminated but can be minimized. In order to minimize the HAZ the following measures can be taken:

- Submerged dielectric should be used rather than flushing on limited area.
- Deionized water is better heat remover than EDM oil.
- The intensity of the spark should be reduced by using low voltage, reduced spark on time and current.

Chapter 7

FABRICATION OF SHAPES AND SAMPLE PARTS

7.1 INTRODUCTION

In the current research several micro shapes and parts were manufactured during the parameter study. After finding the optimal combinations of the parameters and their underlying behaviour, several objects were manufactured to demonstrate the ability of the WEDM operations. Results from the study demonstrated that by enhanced understanding of the interactions of the parameter, it is possible to generate more precise and accurate surfaces and thereby enable better micro precision fabrication.

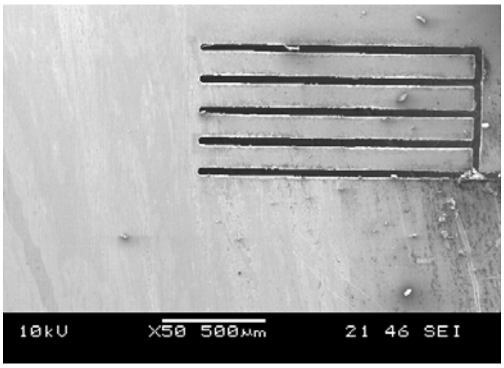
The samples were observed with a Scanning Electron Microscope (SEM). Applying the optimum parameters the microstructures were manufactured with greater accuracy in terms of gap width and surface roughness.

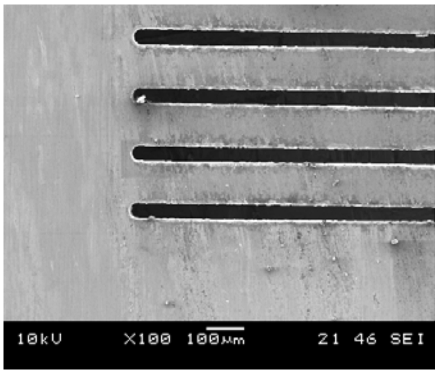
7.2 FABRICATION OF MICRO CHANNELS

A number of micro channels were cut on stainless steel. Parameters used for the machining are:

Table 7.1: Fixed parameters for micro-channels

Wire Speed, Tension	*Voltage Volt*	T_{on}, T_{off} *μs*	*Res. Ω*	*EDM Speed μ/s*	*Short*	*Open*
30%, 35%	80	30, 30	100	5	20	10





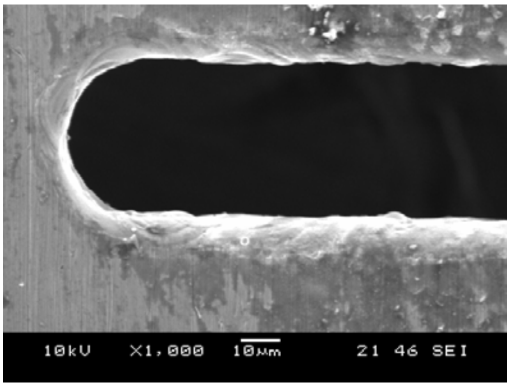


Figure 7.1: closeup SEM image of a single slot

7.3 EFFECT OF DIELECTRIC

7.3.1 Comparison of machining parts machined in oil submerged and no-submerged condition

High aspect ratio microstructures were fabricated using different parameters. Submerge machining condition gave best result in terms of surface finish.

Different conditions of dielectric were used. The first one was done in low pressure dielectric flow, no submersion. The second one was done in submerged condition. But the electrical parameter being the same, the condition is more or less the same. When electrical parameters were changed, primarily R was changed from 33 ohm to 100 ohm; consequently the current reduced from 2.727 to 0.9 ampere. This greatly improved the surface condition as we can see in figure 7.2 B as compared to 7.2 A. Almost no more debris were left on the surface in figure 7.2 B.

Due to high current the gap width is also increased as the crater formed are large at higher current. From the observed surface it could be derived that the current setting should be reduced to as low as possible by applying a higher resistance value. In the current machine the maximum resistance that can be selected is 100 ohm.

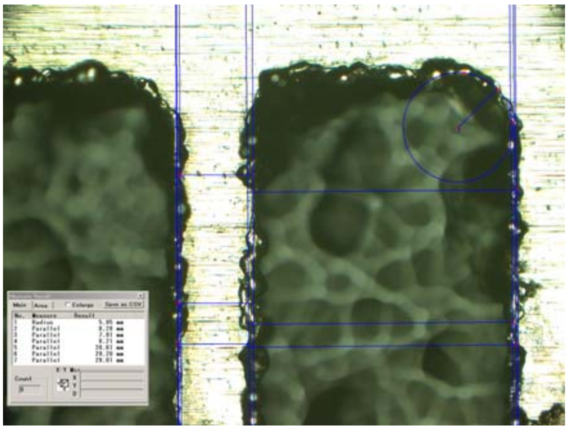


Figure 7.2 A
Machining with no submerge condition

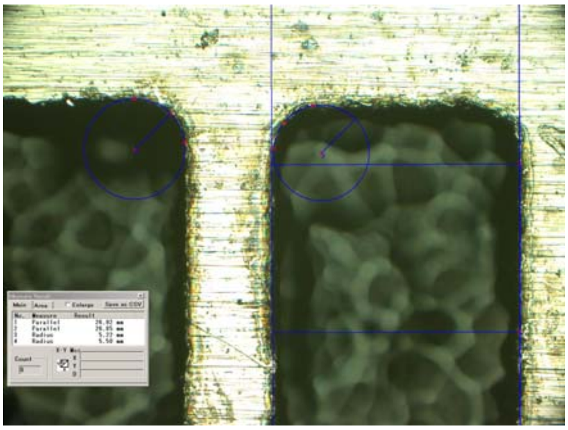


Figure 7.2 B
Submerge in EDM oil

Figure 7.2: Machining with different dielectric condition

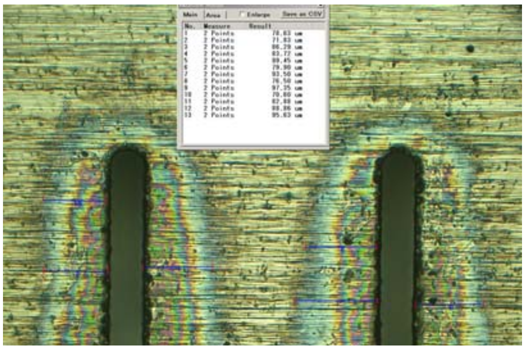
7.3.2 Cutting of slots

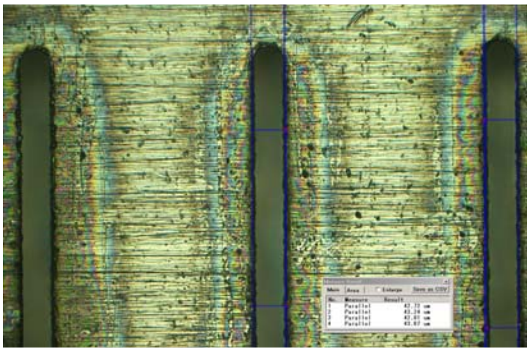
The following section provides the images captured from the Keyence digital microscope of the WEDMed slots. The measurements were taken from the instrument and also from the captured images the damage due to thermal effect is also visible.

In these experiments tungsten wire electrode of 30 µm and 70 µm were used.

Table 7.2: Fixed parameters for cutting slots

Wire Speed, Tension	*Voltage Volt*	T_{on}, T_{off} *µs*	*Res. Ω*	*EDM Speed µ/s*	*Short*	*Open*
30%, 35%	90	15, 30	100	5	20	10





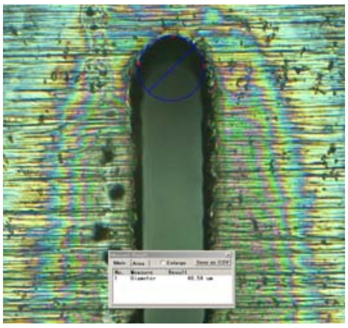


Figure 7.3: Example of slots cut by different diameter of wire

7.3.2 Channels cut using 30 micron wire only

Several micro channels were made using 30 micron tungsten wire. The long channel like structures was cut to observe the accuracy for substantial distance of cut. The sampled machined channels are given in figure 7.4 A and 7.4 B.

Table 7.3: Fixed Parameters for 30 micro wire cut

Voltage	*Resistance*	T_{on}	T_{off}	*Short*	*Open*	*Tension*	*Speed*
80 volt	100 ohm	30 µs	30 µs	20	10	30%	35%

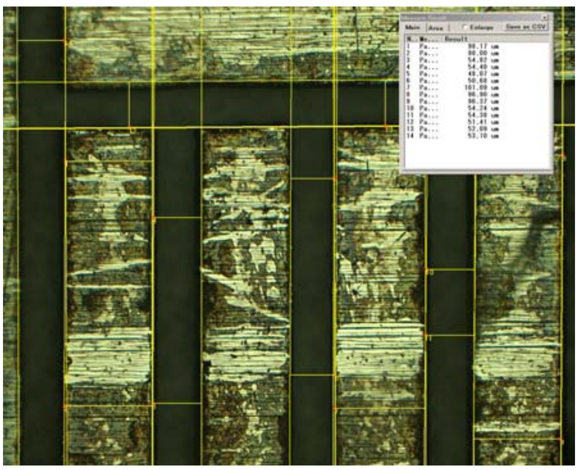


Figure 7.4 A

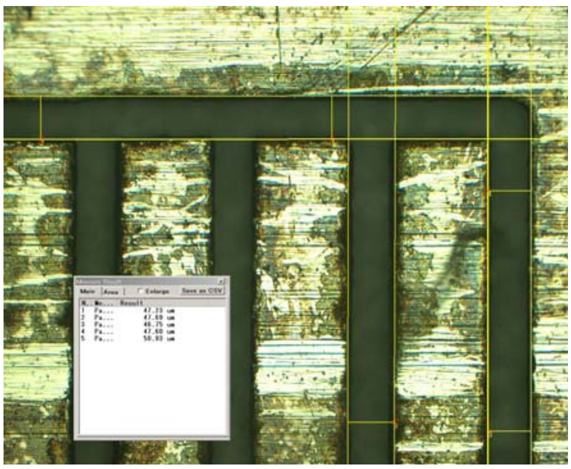


Figure 7.4 B

Figure 7.4: Channel cut with 30 micron wire

7.4 FABRICATION OF MICRO-PARTS: MICRO GEAR

A square micro gear was manufactured to demonstrate the application of WEDM in the real engineering application and micro fabrication. The fabricated micro gear was CNC programmed using only straight line paths, since the interface software was not developed for curved path. In figure 7.5 the gear was machined on stainless steel.

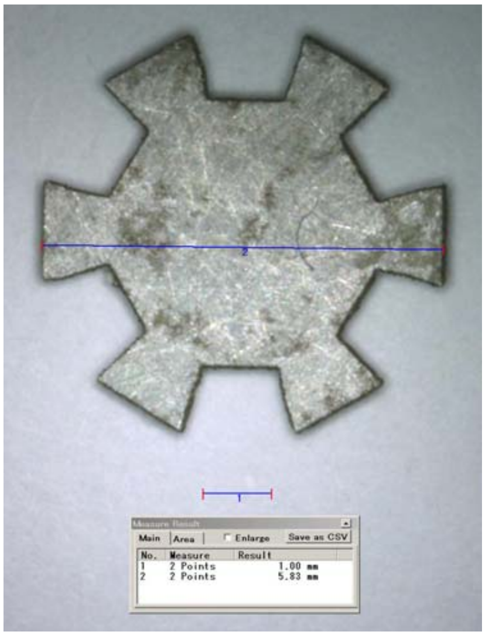


Figure 7.5: Photograph of a WEDMed micro gear of diameter 6 mm (material: stainless steel) Magnification: 25X

7.5 FABRICATION OF MICRO-PARTS: CLOCK DIAL

Two micro parts were fabricated following the shape of clock dial with different set of parameters. The results are presented in the following sections. From the figures 7.6, 7.7, 7.8 and 7.9 – it were evident that the first set of parameter, which had current of 2.72 ampere gives a very poor surface, compared to second set of parameter which use 0.9 ampere.

Table 7.4: Fabrication of clock dial

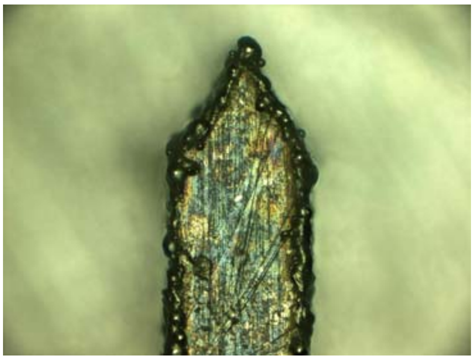
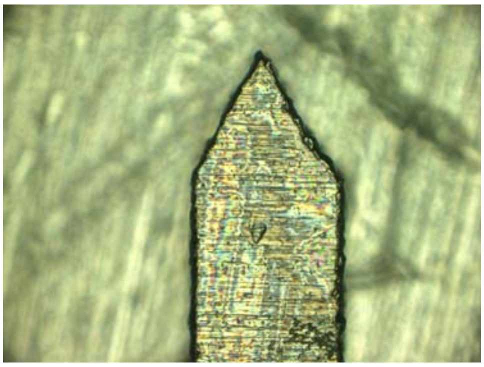
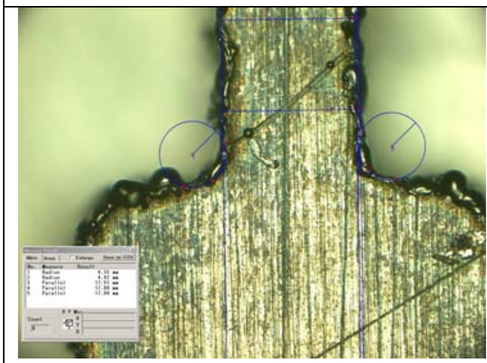
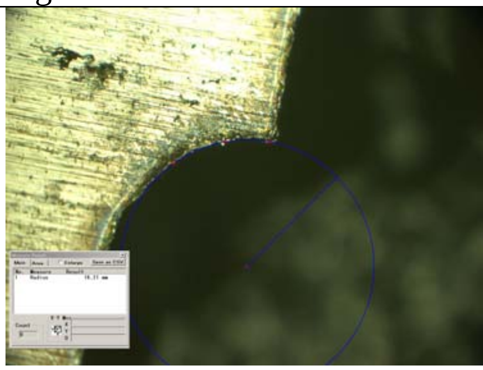
Parameter set 1	Parameter set 2
Voltage 90 volt, Resistance 33 ohm, Current 2.72 amp, T_{on} 10, T_{off} 5, Short 20, Open 10 Speed 30%, Tension 35% Wire 70 micron, oil submerged	Voltage 90 volt, Resistance 100 ohm, Current 0.9 amp, T_{on} 5, T_{off} 5, Short 5, Open 5 Speed 30%, Tension 40% Wire 70 micron, oil submerged
 Figure 7.6A	 Figure 7.6B
 Figure 7.6C	 Figure 7.6D

Table 7.5: Parameters used for the fabrication of the clock dial

Wire dia. (µm)	*Volt. (V)*	*Res. (Ω)*	*T_{on} (µs)*	*T_{off} (µs)*	*Short*	*Open*	*EDM (µm/s)*	*Wire speed*	*Wire tension*
30	90	100	30	30	20	10	3	30%	35%

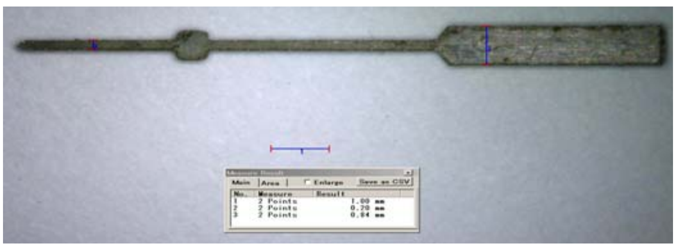


Figure 7.7: High aspect ratio second hand needle of 20 µm Magnification: 50X

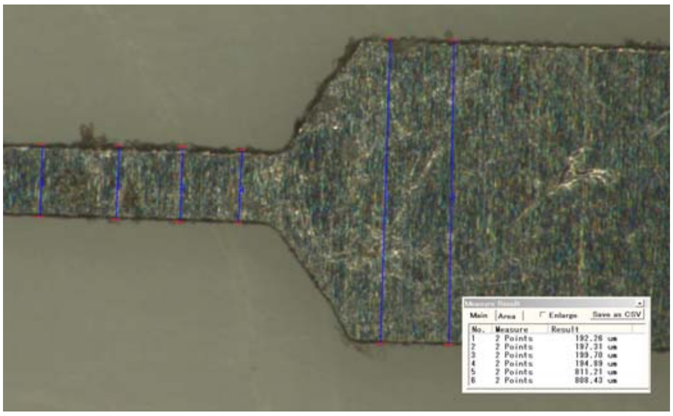


Figure 7.8: Measurement of actual dimensions after machining
Magnification 75X. Machine dimensions: 0.250mm, 0.860mm,
Actual dimensions: 0.196mm, 0.810mm
Average gap width = (250 – 196) – 30/2 = 12 µm

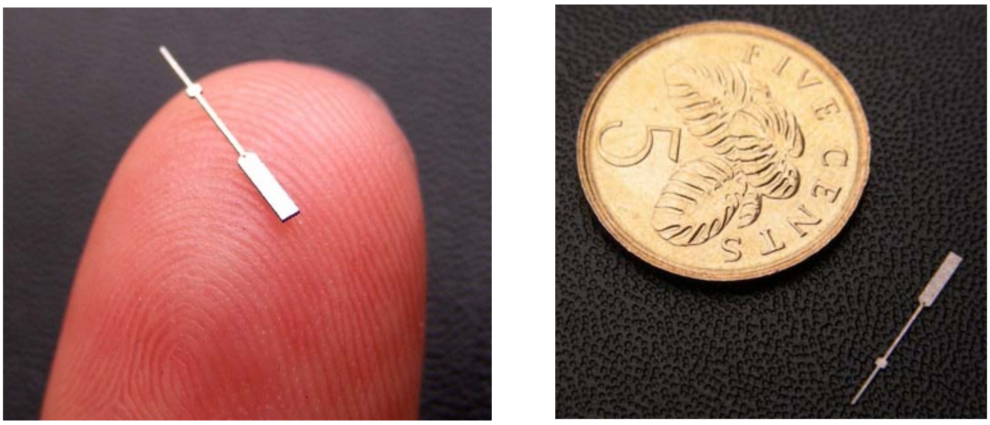


Figure 7.9: The WEMed machined clock dial, for comparison photographed on finger tips

7.6 FABRICATION OF MICRO-PARTS: MACHINING EXAMPLE OF CURVED PATH

Example of an attempt taken to produce curved path after generating the co-ordinates of successive straight path is given here. The curved path program was done separately using C and afterward the generated co-ordinates are given as input to CNC programming.

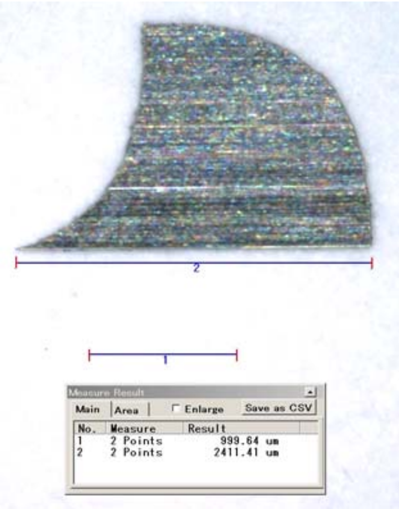


Figure 7.10: Demonstration of a curved cut using the curve program. magnification 50X

7.7 FABRICATION OF MICRO-PARTS: MACHINING EXAMPLE OF NUS LOGO

The National University logo is a Lion - was attempted to be fabricated by WEDM. In order to fabricate the shape of the lion, the machining path was first programmed with the NC code.

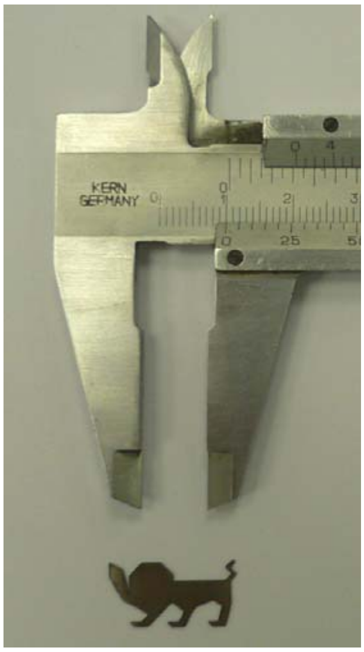


Figure 7.11: A replica of the NUS logo

7.8 CUTTING CHANNELS

Continuous channels were cut at higher voltage and relatively higher spark on time. From the continuation of the channel it was found that the gap of the channel varied. It could be attributed due to the vibration of the wire. Also at the corner there was a radius in the outer side but sharp edge was visible in the inner side.

Table 7.6: Parameters for cutting channel

Wire Speed, Tension	*Voltage Volt*	T_{on}, T_{off} *µs*	*Res. Ω*	*EDM Speed µ/s*	*Short*	*Open*
15%, 15%	150	24, 18	100	10	10	30

Material: Stainless steel (finest tempered), Workpiece thickness 0.30 mm
Electrode: Tungsten wire, diameter 70 micron (0.07 mm)

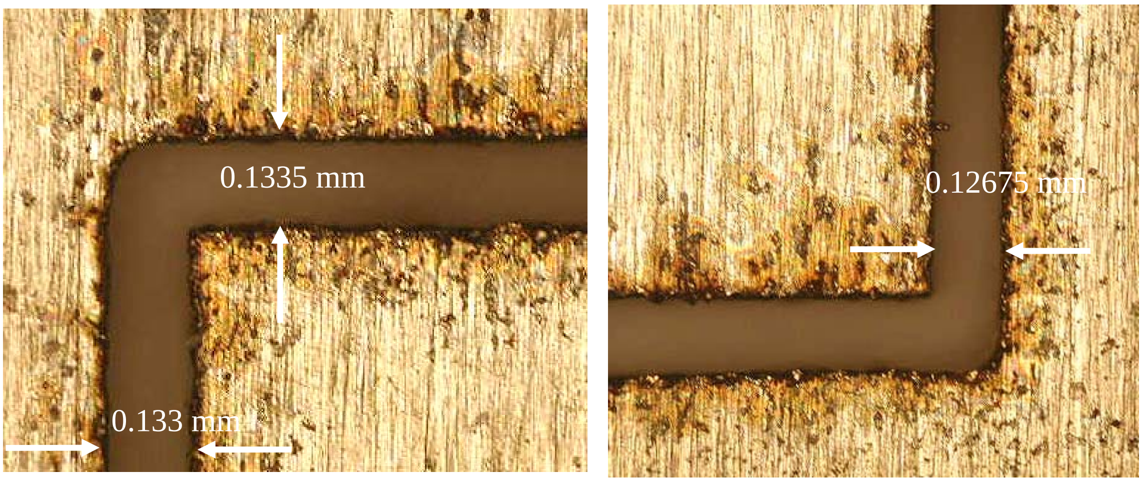


Figure 7.12: Example of cutting channels on stainless steel

Chapter 8

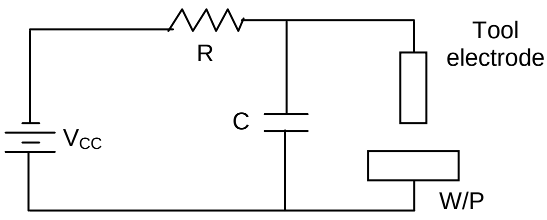
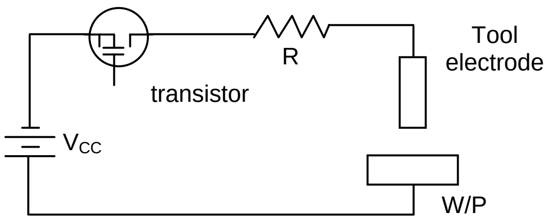
STUDY OF WAVE FORMS

8.1 RC CIRCUIT AND PULSE GENERATING CIRCUIT

8.1.1 Pulse Generator

In the current WEDM machine, the discharge circuit is a transistor based pulse generator. In EDM, two kinds of pulse generator are used: RC pulse generator and transistor type pulse generator. The comparison between the two is given in the table 8.1.

Table 8.1: Comparison between RC and transistor pulse generator

RC Pulse Generator	*Transistor Pulse Generator*
The RC circuit comprises of a d.c. source, a resistor and a capacitor.	The pulse generator circuit comprises of a d.c. source, a resistor and a transistor.
 Figure 8.1 A: RC pulse generator	 Figure 8.1 B: Transistor type pulse generator
Generate small discharge energy by minimizing the capacitance of the circuit.	The dc voltage source is fed via a resistor and an electronic switch (transistor)
Demerits are: 1. Extremely low MRR from its low discharge freq. due to the capacitor charging time required. 2. Uniform surface finish difficult to get since discharge energy varies depending on the electric charge stored in capacitor 3. Thermal damage occurs easily on the w/p.	Compared to RC pulse generator, it has certain advantages: 1. High MRR since no need to charge capacitor 2. Uniform surface finish can be achieved since iso-duration discharge pulse can be generated easily using transistor type generator. 3. Pulse duration and discharge current can arbitrarily be changed.

The voltage/time characteristic for an RC circuit it given in figure 8.2.

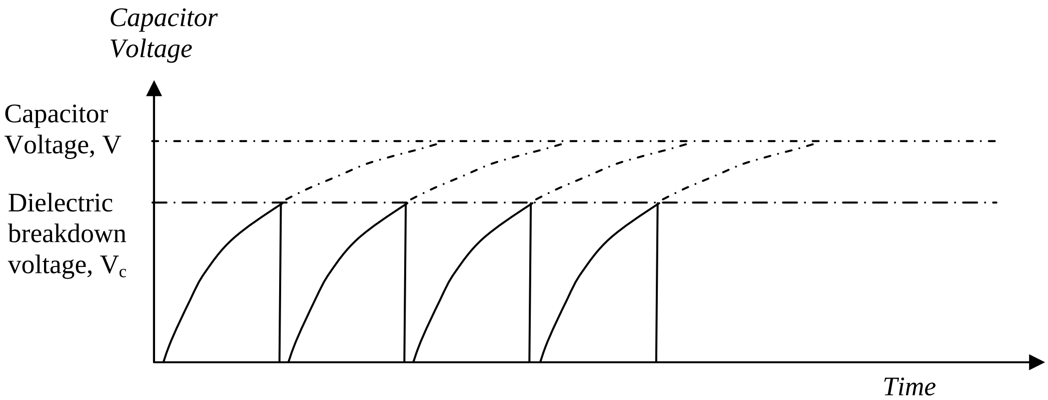


Figure 8.2: Variation of voltage with time using an RC circuit

The transistor based pulse generator differs from an RC circuit comprising only a d.c. source which is fed via resistor and an electronic switch to the machining gap. The voltage/time characteristics is very different than that of RC circuit (figure 8.3).

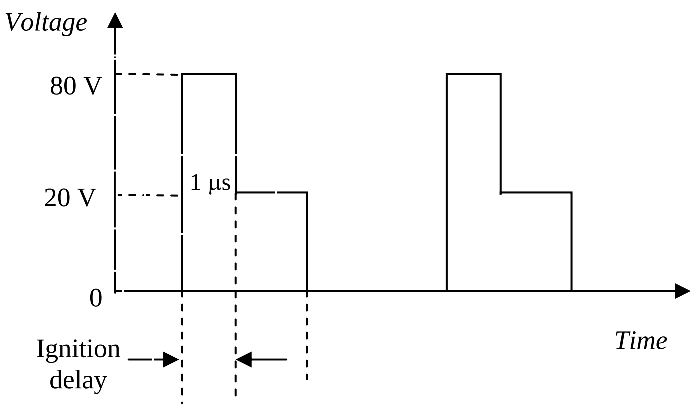


Figure 8.3: Variation of voltage with time using a controlled pulse generator

From the comparison between the voltage/time characteristics of RC and pulse generator it is concluded that duty cycle (ratio of ‘pulse on’ to ‘pulse off’ time) in pulse generator can be much higher than RC circuit. As a result mental removal rate can far exceed those of RC circuit where considerable machining time is lost during capacitor charging.

8.2 ANALYSIS OF THE OSCILLOSCOPE SIGNAL

To analyze overall WEDM conditions, the oscilloscope signal was studied. For this purpose an oscilloscope with data recorder was utilized. The oscilloscope signal was taken from the common ground and one of the voltage polarity on the WEDM device.

The oscilloscope signal was captured for broadly two purposes:

1. In order to understand the time response of the voltage
2. To get an overall picture of the sparking condition that incorporates the stability of spark on and off time, hold condition and short circuiting conditions.

8.2.1 Time Response of Voltage

The time response of voltage during actual machining, short circuiting condition and no machining has distinct feature. When the effective spark occurs, the voltage drops dramatically. For short circuit no machining can occur and voltage remains to the supply voltage. From the recorded oscilloscope picture it becomes clear how these developments occurs during the actual process.

8.2.2. Overall picture of the sparking condition

The macro scenario obtained from the oscilloscope voltage signal gives an overall picture of the electrical condition of the process in real time. The signals were recorded at different current on time and off time combination and the differences were noted. In the oscilloscope picture the top part of the pulse like train denotes continuous sparks. This is the part of the discharges only when machining can occur. It was observed that for some particular pair of current on and off time, the discharge condition was better than others. In these experiments voltage of 80 and resistance of

100 was used. In figure 8.4 the open or retract of the electrode is identified. This is the part of the machining when no effective machining occurs. An example is given in figure 8.5 when the sparks are interrupted due to mostly short circuit condition. Figure 8.6 was captured after reducing the short and open value both to 5. This is when the machining condition seem to improve with less

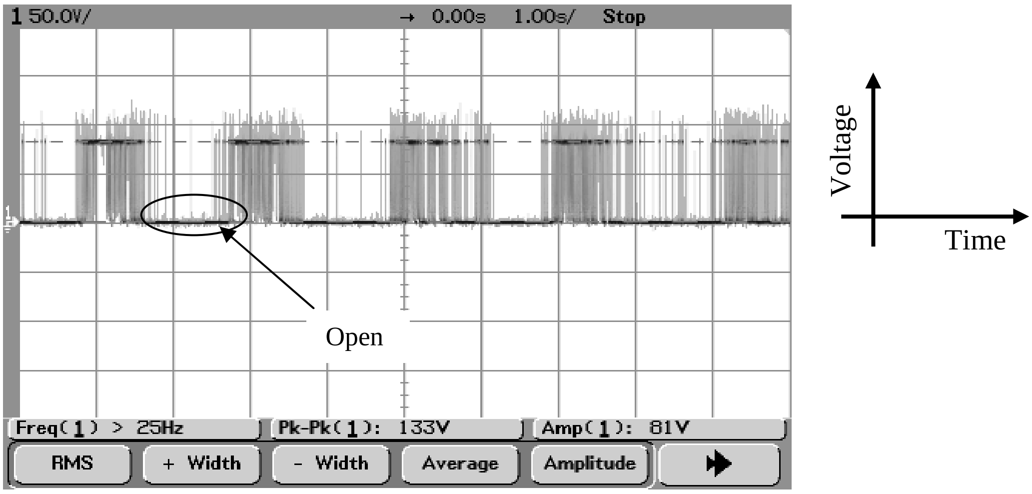


Figure 8.4: Parameter Used: T_{on} 30μs, T_{off} 30μs, Short 20, Open 10

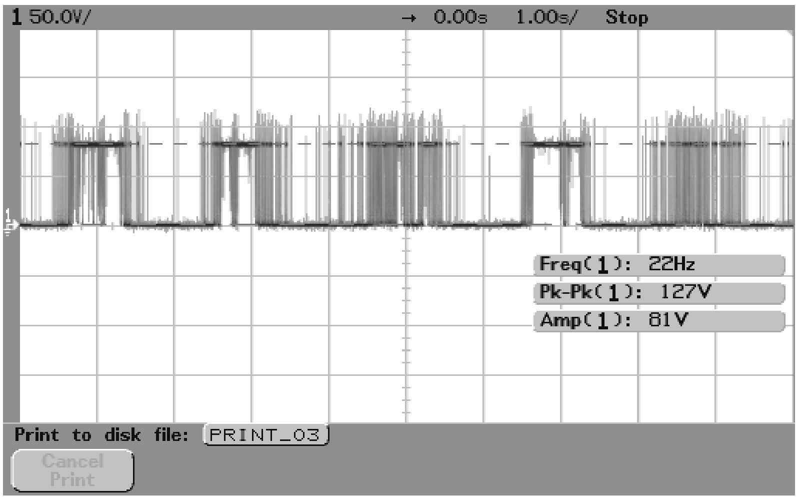


Figure 8.5: Parameters used are T_{on} 15μs, T_{off} 30 μs, Short 20, Open 10

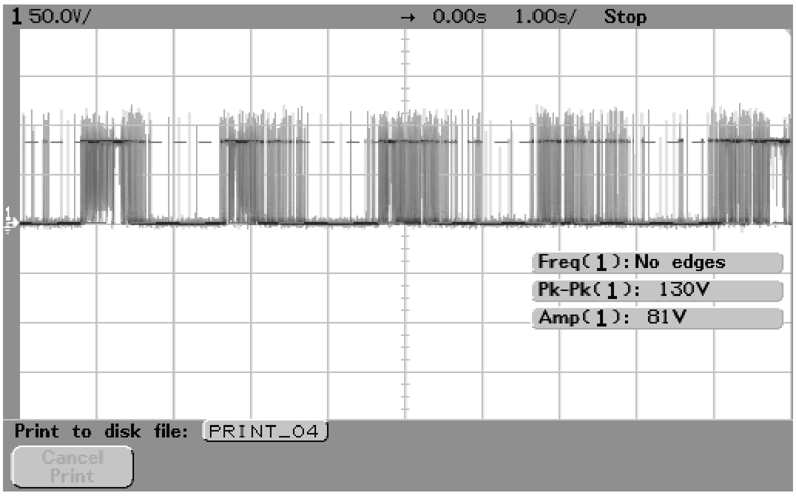


Figure 8.6: Parameters used are T_{on} 15µs, T_{off} 30 µs, Short 5, Open 5

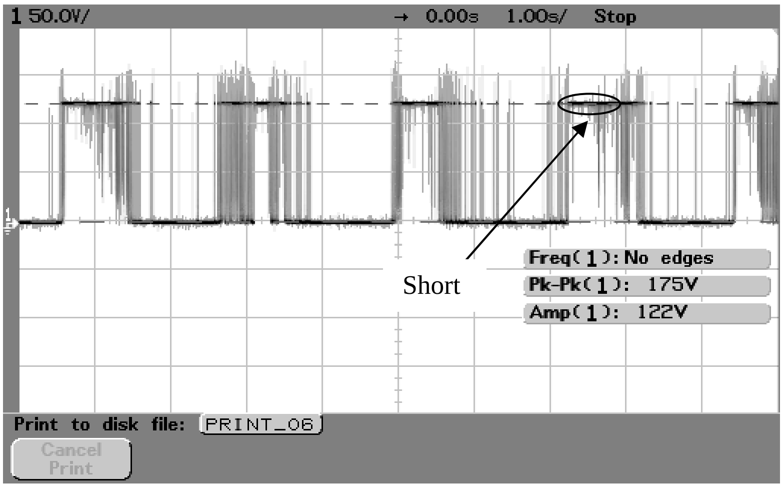


Figure 8.7: Parameter used are T_{on} 30µs, T_{off} 180µs, Short 5, Open 5

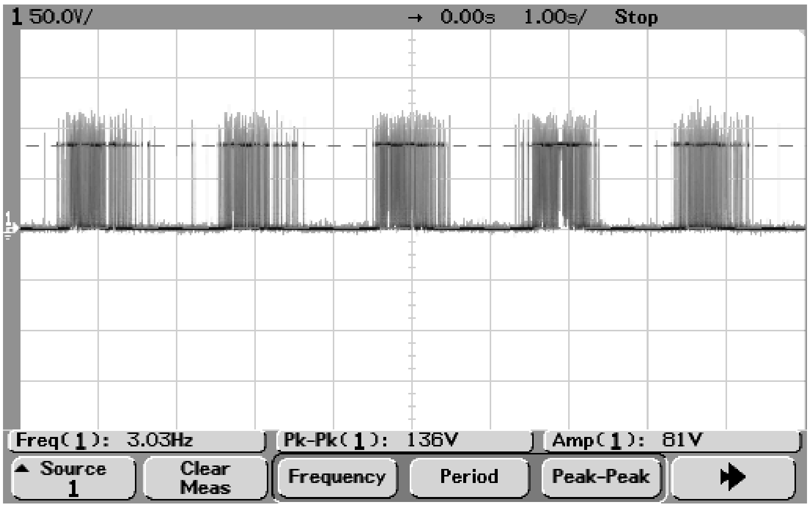


Figure 8.8: T_{on} 15µs, T_{off} 12µs, Short 5, Open 20

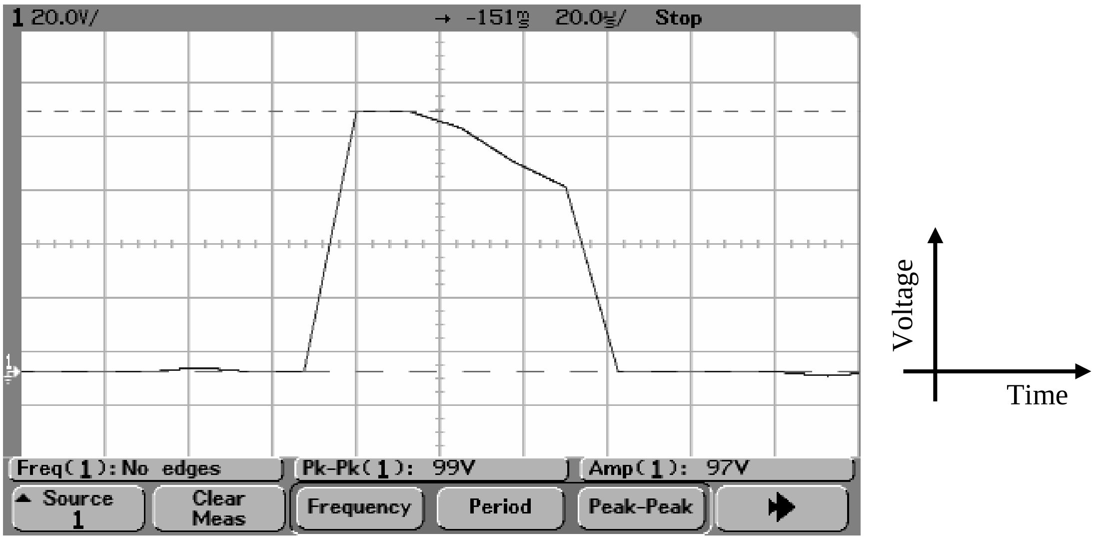


Figure 8.9: Example of voltage pattern in a single spark. The parameters used are: Voltage 90 volt, Resistance 100 ohm, T_{on} 15 µs, T_{off} 30 µs,

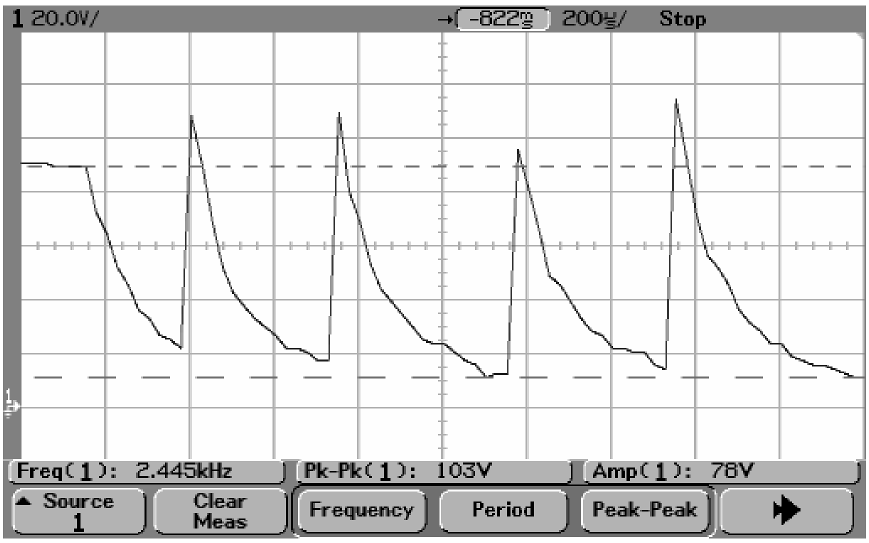


Figure 8.10: The stochastic nature of the sparks having random pattern.

It was found that by increasing the machining off time the efficiency of the machining spark reduced dramatically. A lot of idle and ineffective spark were introduced (figure 8.7).

A very good example of favorable sparking condition was observed in figure 8.8 with negligible short in between the continuous sparks. The combination of parameters was found to be favorable for very efficient machining.

The sparks where analyzed more closely to understand the nature of each spark and how does the voltage signal varies with time. Figure 8.9 and 8.10 demonstrate a single spark and collective sparks respectively.

Chapter 9

RESULTS

9.1 CHALLENGES TO FIND OPTIMUM PARAMETER

Based on the experimental analysis of the effects of different parameters it can be concluded that the primary factors affecting gap width, material removal rate and surface roughness are:

1. Voltage
2. Spark on time
3. Wire Tension
4. Energy (resistance value determines the current and therefore the energy)
5. EDM Speed

Other parameters such as wire run speed, control parameters such as Open and Short detection were also studied. They also have their effects on the process.

A prime target of this research was to determine the optimum parameters. But this task was not straight forward as WEDM is based on sparking phenomena and the nature of the sparks makes the process stochastic. As a result it is almost impossible to come up with some very hard and fast optimum parameter.

Also the objectives for optimal machining conditions are often in conflict. Generally in WEDM operation the following objectives are sought:

1. Good surface finish in terms of surface roughness. The minimum the roughness value, the better.

2. Gap width as low as possible. This enables machining intricate parts.
3. Machining time as high as possible so that machining economy can be maintained.

But unfortunately the machining time objectives have conflict with the first two objectives. In order to achieve a high machining time, therefore a high material removal rate – it means surface quality and gap width minimization have to be sacrificed. For example if a machinist wants to achieve a very high machining rate, the energy input to the machining process needs to be high. So he has to choose high voltage, high current and high spark on time. All of these will contribute to a higher machining speed but will obviously deteriorate other characteristics such as roughness, gap width etc.

Again when a machinist wants to achieve very good surface finish (lowest surface roughness value) he has to choose very less amount of energy input. Thus he has to select very low voltage, low current and low spark on time. As a result the machining time will be very long, though a fine surface finish can be achieved.

For such dilemma, finding the optimum parameter is a fine line of compromise between the priorities. In this research work, major parameters were studied and their degree of contribution to the machining characteristics was studied. The experimental results obtained from this research can aid in taking decisions so that the compromise is made in the light of sound knowledge.

9.2 COMPILATIONS OF THE OPTIMUM PARAMETER RANGE AND VALUES

From the experimental observations, followed by a thorough analysis of the key parameters, the best conditions for MRR, gap width and surface roughness during machining are described in the following section.

9.2.1 Optimize value/ value range for Material Removal Rate

Voltage is the primary factor in affecting the MRR; the larger the value, the higher the MRR at the expense of poor finishing and dimensional inaccuracy. Voltage level is limited by the wire diameter, as smaller wires break easily at higher voltage.

Table 9.1: Optimal range of voltage for fast machining results

Wire Diameter	*Parameter Range*
70 µm	110-130 V
50 µm	100-120 V
30 µm	80-90 V

Resistance works as pivotal factor in determining the amount of energy in the spark, which finally affects the MRR. The lower the value, the higher the MRR at the expense of poor finishing and dimensional inaccuracy. R value is limited to 6.8, 15, 33 and 100 Ω in this machine. However, only 33 Ω and 100 Ω settings can be used as the wire breaks easily at 15 Ω or 6.8 Ω, even for 70 µm wire.

Table 9.2: Optimal value of resistance for fast machining results

Wire Diameter	*Parameter value*
70 µm	33 ohm
50 µm	
30 µm	

Spark on and off time are also major factors in affecting the MRR; T_{on} should have a larger value so that the current on time is longer, while T_{off} should not have a very large value to reduce the idle time when no machining occurs. However T_{off} cannot be 0 or too small as time is needed for the cutting area to regenerate the ideal conditions for sparking again. Increase in T_{on} is limited by the wire diameter, as smaller wires break easily at higher T_{on}.

Table 9.3: Optimal value of Spark on and off time for fast machining results

Wire Diameter	*Parameter Range*
70 µm	T_{on} / T_{off} : 20-35 / 5
50 µm	T_{on} / T_{off} : 15-20 / 5
30 µm	T_{on} / T_{off} : 10-15 / 5

Both short and open are not very significant factor in affecting the MRR, yet they have some implications. For smaller diameter wires short value should be higher to increase the MRR, and the open value (dependant on the T_{on}/T_{off} cycle) should be smaller to increase MRR. By increasing the short detection parameter, frequent detection of short can be avoided. Thus it helps faster machining. Again open value should be higher to reduce idle time during the machining process. A short value of 20 and an open value of 10 were found to be quite satisfactory in terms of machining result.

Wire speed is again not a significant factor in affecting the MRR. The speed of the wire should not be too high to avoid the wastage of the wire. At very slow speeds the wire tends to break more often, since the same region gets eroded more, reducing the tensile strength of the wire. A wire speed of 30% (4.04 rpm) was found to be optimal.

Wire tension is also not a significant factor in affecting the MRR. The tension of the wire should not be too high to prevent the wire from breaking easily. However, low wire tension might reduce the MRR due to more frequent short circuit as the wire may vibrate easily at lower tension. The optimum wire tension was found to be around in the range of 35% to 40%.

EDM speed is a less significant factor in affecting the MRR; controls the rate at which the wire approaches the work piece, but will not the cut unless sufficient spark discharge is produced, which is not dependant on the EDM speed. EDM speed typically in the range of 5 to 12 μm/s was found to yield better results.

Dielectric condition is a secondary factor for MRR. Submerged flushing with oil reduces the MRR rate significantly, compared to normal flushing. Deionized water removes debris from the cutting area better than oil, slightly increasing the MRR. For faster machining rate deionized water with normal jet flushing is recommended. It was observed that using EDM oil as dielectric gives better surface integrity (surface roughness) as compared to deionized water.

It is obvious that larger wire diameter will contribute to higher machining rate. Thus wire diameter is a primary factor for MRR; larger wire diameter can release a larger discharging energy, hence enabling a larger spark to remove more material. The highest wire diameter available was 70 μm and is recommended for higher MRR. But this again limits the accuracy.

9.2.2 Optimize value/ value range for gap width

Voltage is the primary factor in affecting the gap width; the smaller the voltage, the less energy available for sparking hence contributing to smaller gap width. However, machining time is sacrificed for small gap width. The optimum range was obtained around 70 to 80 volt.

Resistance is a primary factor in affecting the gap width; Resistance level set at 100Ω gives smaller gap width that is usually less than 10μm, depending on the diameter of wire.

For gap width, spark on and off time are primary factor. A longer T_{on} time allows for more sparking to occur, hence increasing the gap width. T_{off} time barely affects the gap width, since no spark is created during T_{off}. The optimum value obtained are in the range between 15 to 30 μs

Wire speed is secondary factor in affecting the gap width; slow wire speed will cause the same area of wire to experience more discharge energy (reducing the wire diameter) hence reducing the consistent gap between the wire and the work piece. This will cause uneven gap width along the machining path. However, high wire speed increases the cost of manufacturing. A value of 35% seems to give consistent results.

Wire tension is one of the major factors in affecting the gap width; low tension value of the wire will result in excessive sideway vibration of the wire, as was observed from high speed camera; hence affecting the gap width. Wire should be taut to prevent wire from vibrating. Tension value of 40% to 45% generates good gap width.

EDM Speed is not a significant factor in affecting the gap width; the EDM speed does not affect the discharging energy, hence having no effect on the gap width.

Dielectric fluid and flushing condition are primary factor in affecting the gap width; submerged operation improves the surface integrity, reduces the HAZ and also helps the cutting area to cool faster compared to flushing. However, water helps to clear the debris faster than oil, and also absorbs the high temperature more easily compared to oil. Oil and submerged flushing are preferred, since gap width and surface integrity is an important aspect of good quality finishing.

Wire diameter is another major factor in affecting the gap width. Accuracy of the wire diameter is important. A smaller wire diameter contributes to a smaller gap width. Thus the lowest wire diameter gives the better gap width.

9.2.3 Optimize value/ value range for surface roughness

Voltage is the primary factor in affecting the surface roughness. A lower voltage level is recommended. Thus from experimental results the voltage range from 90 to 130 volt can be selected.

Surface roughness value improves with increasing resistance, and therefore with decreasing current. The highest resistance available in the machine was used (100 ohm).

Wire speed is a less important factor. From experimental results it was found that increasing wire speed contributes to better surface roughness. A higher wire speed such as 50% is recommended.

9. 3 SUMMARY OF: BEST RESULTS ACHIEVED

In the following tables 9.4, the best results obtained in terms of gap width, material removal rate and surface roughness are presented.

Table 9.4: Best Results achieved at a glance

Objective	*Voltage*	*Res.*	T_{on}, T_{off}	*Wire Speed, Tension*	*EDM speed*	*Short*	*Open*	*Dielectric condition*	*Wire Dia.*	*Result*
	Voltage	Ohm	µs	%	µ/s	Cycle time	Cycle time		µm	
Gap width	120	33	15, 12	30, 40	10	5	5	Oil, Submerge	50	2 µm
Material Removal Rate	150	33	30, 30	40, 40	10	12	8	Water, Normal flushing	70	10747.66 $\mu m^2/s$
Surface Roughness	90	100	30, 30	40, 40	10	12	8	Oil, Submerge	50	0.49731 Ra, µm

For the sake of comparison of current research results, some of the results achieved by other researches on WEDM are worth mentioning here. In the following table few such works are presented.

Table 9.5: Summarization of literature results in terms of achievement in surface finish, machining rate and kerf, wire diameter

Ref.	*Wire material and diameter*	*Work material*	*Surface Finish, μm (R_a)*	*MRR or VMRR*	*Kerf mm*	*Parameters used*
Liao et al, 2004			0.22			Ton 0.05 μs, Toff 8, 100V, 100 Ohm, 4 mm/min (feed)
Hascalyk 2004			1.28-1.3			
Hewidy et al., 2005	Brass CuZn37, 0.25 mm	Inconel 601 (Ni 61%, Fe14%, Cr 23%, Al1%)	0.9-1.0	7.2 (mm^3/m)		Ton 3.0 μs, Toff 1.0=5.0, I=3.0-7.0 **Best R_a :** 5 amp, Ton 3, Toff 1, Wire Tension 9, Water pressure 0.5 MPa **Best VMRR:** 6 amp, Ton 3, Toff 3, Wire Tension 7, Water pressure 0.5 MPa
Hwa Yan et al., 2005	Brass, 0.25 mm	10 and 20% vol Al_2O_3 reinforced 6061 Al alloy based composite and matrix material	2.1	130 (mm^2/m)	0.263	
Huang et al., 1999	Brass, 0.25 mm	SKD11 alloy steel	1.42			Ton 0.1 μs, Toff 8, 95V
Liao et al., 1997	Brass, 0.25 mm	SKD11 alloy steel				
Gokler, 2000	Brass, 0.25 mm	1040 Steel, Tool Steel	2.58 horz 2.36 vert			40V, 7amp, feed 1.232 mm/min
Huang, 2003	Brass, 0.25 mm	SKD11 alloy steel	2.483	32.50 (mm^3/m)	0.390	95V, Ton 0.7, Toff 20.8, F 2.5 mm/min

Tosun, 2004	Brass, 0.25 mm	AISI 4140 Steel			0.29 2	100V, Ton 0.3μs, Toff 16μs

Comparing with other results as presented in table 9.5 and the current research results accomplishments as stated in table 9.4, it can be seen that this research have achieved significant improvements. Compared to previously achieved minimum gap width of 6.5 μm, in the current research best achieved gap with was 2 μm. Also the best surface roughness of Ra, 0.497 μm is better than most of the previous results. Only in the case of material removal rate in current research the rate is lower since the imparted energy was considerably less.

9.4 PROBLEMS ENCOUNTERED

Some of the problems encountered during the work are mentioned in the following sections.

9.4.1 Disadvantage of transistor based pulse generating circuit

Because of the inherent problem of pulse generating discharge circuit, it doesn't provide optimum result for low energy discharge. As Y. S. Liao [2004] mentioned in his paper that pulse-generating system is not suitable for finishing process, since the energy generated by the high-voltage sub-circuit is too high to achieve a desired fine surface, no matter how short the pulse-on time is assigned.

9.4.2 Problems related to flushing

Currently the device uses dielectric at a low pressure drive by a nozzle and it is only directed from the top. As a result the debris in the micro-gap are not properly removed, which lead to short-circuiting, bad surface quality and wire breakage. Also the heat affected area is more on the bottom surface of the workpiece for the absent of the dielectric fluid. Lack of dielectric pressure and inability to enclose the wire electrode and workpiece is a major problem that requires careful attention.

9.4.3 Wire vibration

From the observation of the wire vibration with the help of high speed camera (figure 9.1), it was found that the maintaining of tension is not consistent. The vibration of the wire during machining contributes partly to the uneven surface roughness and gap width. At higher voltage and T_{on} values, it was observed a greater uneven distribution of the surface during machining and these could partly be due to increased in the frequency of vibration in the wire.

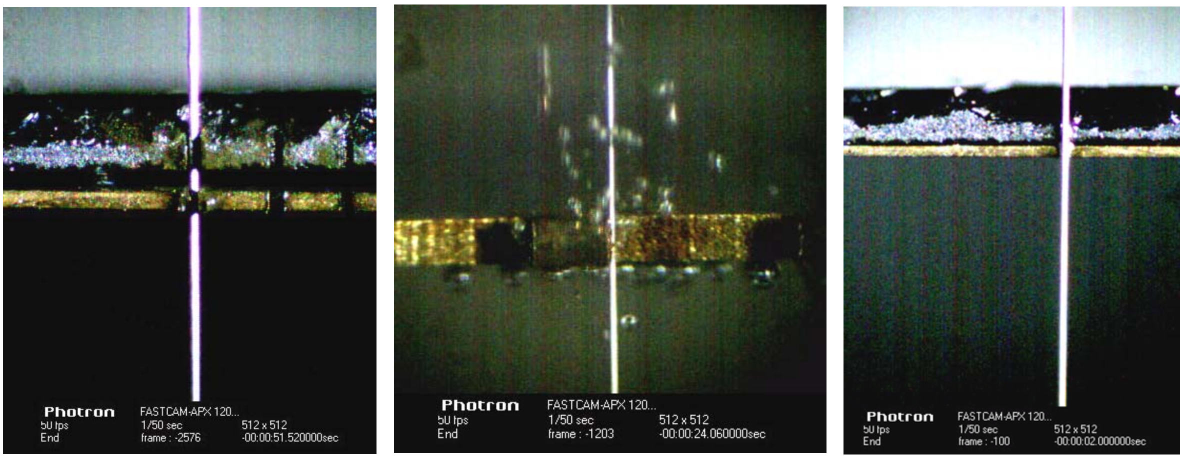


Figure 9.1: Captured still images from high speed camera video of WEDM

9.4.4 Wire transport method

The wire moves freely over the source rollers and open grooves, which with time wear out and slowly change the wear transport path. This introduces the possibility of machining path error. Also the guiding system is not able to maintain the wire position with tight accuracy. This may contribute to over-cut or wider gap width.

Chapter 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 MAJOR CONTRIBUTIONS

In this research work, the major contributions can be divided into 4 parts:

- From conceptualization to design of a μWEDM device
- Development of the μWEDM device and integrating it with the multi-process CNC machine
- Experimental investigation on the major parameters of μWEDM
- Finding optimal parameters to achieve desired machining characteristics

The main contributions of this study are summarized as follows:

10.1.1 From conceptualization to design of μWEDM device

The μWEDM was first conceptualized from scratch. Once the requirement of the device was realized, the concepts were followed by design. Different parts of the device were designed keeping in mind the application, requirements and limitations.

10.1.2 Development of the μWEDM device and integration with the CNC machine

After finishing the design on the paper and inside design software package the fabrication phase of the work was conducted. The designed μWEDM device was integrated with the CNC machine and initial calibration was done.

10.1.3 Experimental investigation on the major parameters of μWEDM

In WEDM the machining characteristics are mostly influenced by the parameters selected. Experimental investigation for the parameters such as voltage, current and energy, spark on and off time, EDM speed, wire speed and tension, open and short parameters, dielectric effect were taken into consideration.

10.1.4 Investigation for optimal parameter

After the primary and secondary parameters and their effect on the machining characteristics were identified, efforts were undertaken to identify the range of optimal parameter range. The inherent unpredictable nature of the sparking phenomena causes the identification of optimal parameter more challenging. Thus it was recommended that to achieve different objectives a fine line of compromise between the parameters is necessary.

To identify the optimal parameters three main machining characteristics were investigated which are gap width, machining time or material removal rate and surface profile or roughness. Effects on machining characteristics were observed as each parameter was tested in a series of controlled experiments. Micro parts of different shapes were also manufactured to demonstrate the ability of the WEDM machine.

Finally the investigated optimum parameters are compiled in a compact table which can be used as a guide for optimum machining combination for this particular μWEDM device. Also the features in general of the interaction of different parameters to machining characteristics can be applied to μWEDM process in general.

10.2 RECOMMENDATIONS FOR FURTHER IMPROVEMENTS

During the research it was observed that the designed WEDM device can be further modified to incorporate some other facilities and to improve machining accuracy. Due to time constraints, all of these improvements could not be accommodated but these recommendations can be used as a study guide to the next research in the forward direction.

10.2.1 Possibility to switch from transistor based circuit to RC circuit

The current μWEDM machine uses a pulse generator to generate spark discharges and experiments so far have been able to produce a minimum gap width of 2 µm. But this achievement is not consistent. Rather gap width mostly remains around 10 µm or even higher.

Making use of a Resistance-Capacitance (RC) circuit, it is possible to produce even better surface finish and generate a smaller gap width. This is due to the ability of an RC-circuit to produce smaller discharge energy, and hence create a smaller crater during machining. Even modern EDM machine manufacturers now prefer RC circuits for its better machining achievement than transistor based discharge circuit.

10.2.2 Flushing device for WEDM device

It is recommended that a compact flushing device be incorporated in the device replacing the current low pressure nozzle drive flushing. Equal pressure from all side on the wire needs to be maintained so that the machining path does not get changed because of variable pressure from different sides. The attachment has to be carefully designed so as to prevent any interference with the movement of the WEDM machine.

10.2.3 Wire vibration

Reduction of the vibration can be done by taking a number of measures. The strategy to control the tension of the wire can be re-evaluated. A preliminary study was done and it was found that the placement of anti-vibration foam along the wire-path causes the gap width to decrease, as opposed to not placing any foam along its path. However, the position and material of these anti-vibration foams has to be further investigated, as in some positions the foam actually causes the gap width to increase.

10.2.4 Wire transport mechanism

Instead of letting the wire move freely over grooves and rollers, closed wire guides can be placed to ensure that the movement path of the wire is consistent. In die sinking EDM long electrode are generally supported by closed electrode guides made of wear resistant materials such as ceramic. Such guides can be incorporated in the device to improve accuracy in the wire transport mechanism.

REFERENCES

Arunachalam, C., Auila, M., Bozkurt, B. and P. T. Eubank. Wire vibration, bowing and breakage in wire electrical discharge machining, Journal of Applied Physics, 89 (8), 2001.

Balleys, F. Removal rate vs accuracy in wire cuts. ISEM V, pp.157–159. 1997.

Bannerjee, S., Prasad, B.V.S.S., Mishra, P.K., Analysis of three dimensional transient heat conduction for predicting wire erosion in the wire electrical discharge machining process. Journal of Material Processing Technology, 65, pp.134–142. 1997.

Corbett, J., McKeon, P.A., Peggs, G.N. and R. Whatmore. Nanotechnology: international developments and emerging products, Annals of CIRP, Vol. 49, pp. 523–546. 2000.

Dekeseyer, W., Snoeys, R. and M. Jennes. A thermal model to investigate the wire rupture phenomenon for improving performance in EDM wire cutting, Journal of Manufacturing Systems, 4, pp.179–190. 1985.

Faulk, N. M. Electrical discharge machining of advanced ceramics. Proceedings of the International Conference on Machining of Advanced Materials, Gaithersbug, MD, pp. 525-534. 1993.

Fukuzawa, Y. et. al. Electrical discharge machining of insulator ceramics with a sheet of metal mesh, Proceedings of the ISEM-II, pp. 173-179. 1995.

Gatto, A., and L. Iuliano. Cutting Mechanisms and Surface Features of WED Machined Metal Matrix Composites, Journal of Material Processing Technology, 65, pp.209-214. 1997.

Guitrau, E. Bud. The EDM Handbook, Cincinnati : Hanser Gardner Publications, 1997.

Guo, Z. N., Yue, T. M. and W. S. Lau. Computer simulation and characteristic analysis of electrode fluctuation in wire electric discharge machining, Journal of Materials Processing Technology, 142, pp.576-581. 2003.

Hascalyk, Ahmet and Ulas Caydas. Experimental study of wire electrical discharge machining of AISI D5 tool steel, Journal of Materials Processing Technology. 148, pp.362-367. 2004.

Heeren, Paul-Henri, Reynaerts, Van Brussel, Dominiek Hendrik, Beuret, Cynthia Larsoon, Olle and Axel Bertholds. Microstructuring of silicon by electro-discharge machining (EDM) – part II: applications. Sensors and Actuators A, 61, pp.379-386. 1997.

Hewidy, M. S., T. A. El-Taweel, M. F. El-Safty. Journal of Material Processing Technology xxx . xxx-xxx (article in press). 2005.

Ho, K. H., Newman S. T, Rahimifard, S and R. D. Allen. State of the art in wire electrical discharge machining. International Journal of Machine Tools & Manufacture, 44, pp.1247-1259. 2004.

Hwa, Yan Biing, Tsai, Hsien Chung, Huang, Fuang Yuan and Lee Long Chorng. Examination of wire electrical discharge machining of Al_2O_3 p/6061 Al Composites, International Journal of Machine Tools & Manufacture, 45, pp.251-259. 2005.

Jennes, M., Snoeys, R., and W. Dekseyer. Comparison of various approaches to model the thermal load on the EDM wire electrode, Annals of the CIRP, 33 (1), pp.93–98. 1984

Kinoshita, N., M. Fukui and G. Gamo. Control of wire-EDM preventing electrode from breaking, Ann. CIRP, 31 (1), pp.111-114. 1982.

Konig,W. and U. Panten. Effective machining process even for ceramic materials, Proceedings of the International Symposium of Electrical machining, ISEM-X, Magdeburg, pp. 269-286. 1992.

Kunieda, Masanori and Satoyuki Ojima. Improvement of EDM efficiency of silicon single crystal through ohmic contact, Journal of International Societies for Precision Engineering and Nanotechnology, 24, pp.185-190. 2000.

Lagne, H. H., Masuzawa, T. and M. Fujino. Modular method for microparts machining and assembly with self-alignment, Ann. CIRP 44, pp.173-176. 1995.

Laio, Y. S. and J. C. Woo. The effects of machine settings on the behaviour of pulse trains in WEDM process, Journal of Material Processikng Technology, 71, pp.433-439. 1997.

Lang, W. Reflexions on the future of microsystems, Sensor and Actuators, 72 pp.1–15. 1999.

Liao, Liao, Yunn-Shiuan, Chen, Shun-Tong and Chang-Sheng Lin. Development of a high precision tabletop versatile CNC wire-EDM for making intricate micro parts, Journal of Micromechanics and Microengineering. 15, pp. 245-253. 2005.

Liao, Y. S. and Y. P. Yu. The energy aspect of material property in WEDM and its application. Journal of Materials Processing Technology, 149, pp.77-82, 2004.

Liao, Y. S., Chu, Y. Y. and M. T. Yan. Study of wire breakage process and monitoring of WEDM, International Journal of Machine Tools Manufacture. 37 (4), pp.555-567. 1997.

Liao, Y. S., Huang, J. T. and C. S. Su. A study on the machining-parameters optimization of wire electrical discharge machining, Journal of Materials Processing Technology. 71, pp.487-493. 1997.

Liao, Yunn-Shiuan, Chen, Shun-Tong and Lin Chang-Sheng. Development of a high precision tabletop versatile CNC wire-EDM for making intricate micro parts, Journal of Micromechanics and MicroEngineering. 15 pp.245-253. 2005.

Liao, Yunn-Shiuan, Chen, Shun-Tong, Lin, Chang-Sheng and Tzung-Jen Chuang. Fabrication of high aspect ratio microstructure arrays by micro reverse wire-EDM. Journal of Micromechanics and Microengineering, vol. 15, pp. 1547-1555. 2005b.

Luo, Y. F. , Chen, C. G. and Z. F. Tong. Investigation of silicon wafering by wire EDM, Journal of Material Science, 27, pp.5805-5810. 1992.

Luo, Y. F., Chen, C. G. and Z. F. Tong. Investigation of silicon wafering by wire EDM, Journal of Materials Science. 27, pp.5805-5810. 1992.

Luo, Y. F., Chen, C. G. and Z. F. Tong. Investigation of silicon wafering by wire EDM. Journal of Materials Science, 27, pp.5805-5810. 1992.

Luo, Y. F., Chen, C. G. and Z. F. Tong. Investigation of silicon wafering by wire EDM. Journal of Materials Science, 27, pp.5805-5810. 1992.

Luo, Y. F., Chen, C. G. and Z. F. Tong. Silicon thin silicon wafer by wire EDM cutting. Proce. 10th Int. Symp. Electromachining. Magdeburg, Germany, pp.287-294. 1992.

Madou, M.J. Fundamentals of Microfabrication, CRC Press, Boca Raton, 1997.

Masaki, T., Kawata, K. and T. Masuzawa. Micro electro discharge machining and its applications. Proc. IEEE Micro Electro Mechanical System, Napa Valley, CA, USA. pp. 21-26. 1990.

Masaki, T., Kawata, K. and T. Masuzawa. Micro electro discharge machining and its applications, Proc. IEEE Micro Electro Mechanical System, Napa Valley, CA, USA. pp.21-26. 1990.

Miller, Scott F., Kao, Chen-C., Shih, Albert J. and Jun Qu. Investigation of wire electrical discharge machining of thin cross-sections and compliant mechanisms, International Journal of Machine Tools & Manufacture, 45, pp.1717–1725. 2005.

N. Mohri, et al. Assisting electrode method for machining insulating cermaics, CIRP Ann. 45 (1) pp. 201-204. 1996.

Pachon, M.C. Thermomechanical model to avoid wire breakage in wire electro-discharge machining, MS thesis, Storrs, University of Connecticut, CT, 1997.

Pandit, S. M. and K. P. Rajurkar. A Stochastic approach to thermal modeling applied to electro-discharge machining, Trans. ASME J. Heat Trans., 105, pp.555-558. 1983.

Peng, W. Y. and Y. S. Liao. Study of electrical discharge machining technology for slicing silicon ingots, Journal of Materials Processing Technology. 140, pp. 274-279. 2003.

Peng, W. Y. and Y. S. Liao. Study of electrical discharge machining technology for slicing silicon ingots, Journal of Materials Processing Technology. 140, pp.274-279. 2003.

Qu, Jun and Albert J. Shih. Development of the Cylindrical Wire Electrical Discharge Machining Process, Part 2: Surface Integrity and Roundess. Transactions of ASME. 124, 2002.

Rajurkar, K. P. and W. M. Wang. Ann. CIRP. Vol. 40, pp. 219-222, 1991a.

Rajurkar, K. P. and W. M. Wang. On-line monitor and control for wire breakage in WEDM, Ann. CIRP, 40 (1), pp. 219-222. 1991.

Rajurkar, K. P. and W. M. Wang. Proc. 1992 Pacific Conf. on Manuf. pp. 346-353, 1992.

Rajurkar, K. P., and G. F. Royo, Effect of R. F. control and orbital motion on surface integrity of EDM components, Journal of Mechanical Work Technology. 20, pp.341-352. 1989.

Rajurkar, K.P., Wang, W.M. and Y.H. Huang, Monitoring and control strategy for wire breakage in WEDM. Transactions of NAMRI/SME, 19, pp.148–153. 1991.

Ramulu, M., Jenkins, M. G., and J. A. Daigneanult. Spark-Erosion Process Effects on the Properties and Performance of a Tib_2 Particulate-Reinforcement/SiC Matrix Ceramic Composite. Ceramic. Eng. Sci. Proc., 18(3), pp.227-238. 1997.

Reynaerts, Dominiek, Heeren, Paul-Henri and Hendrik Van Brussel. Microstructuring of silicon by electro-discharge machining (EDM) – part I: theory, Sensors and Actuators A, 60, pp.212-218. 1997.

Saha, S., Pachon, M., Ghoshal, A. and M.J. Schulz. Finite element modeling and optimization to prevent wire breakage in electro-discharge machining, Mechanics Research Communications, 31, pp.451-463. 2004.

Schumacher, M. Bernd, After 60 years of EDM the discharge process remains still disputed. Journal of Material Processing Technology, 149, pp.376-381, 2004.

Scott, D., Boyina, S., and K. P. Rajurkar. Analysis and optimization of parameter combinations in wire electrical discharge machining, International Journal of Production Research, 29 (11), 2189–2207. 1991.

Snoeys, R. and F. Van Dijck. Investigation of EDM operations by means of thermo-mathematical models, Ann. CIRP, 20 (1), pp.35-36. 1997.

Spur, G. and J. Schonbeck. Anode erosion in wire EDM – a theoretical model, Ann. CIRP 42 (1) pp.253-256. 1993.

Staufert, G., Dommann, A. and D. Lauger. Behaviour of silicon spring fabricated by wire electro-discharge machining, Journal of Micromechanical and Microengineering, 3, pp.232-235 1993.

Staufert, Gerhard; Dommann, Alex and Dieter Lauger. Behaviour of a silicon spring fabricated by wire electro-discharge machining. Journal of Micromechanics and Microengineering, 3, pp.232-235. 1993.

Tosun, Nihat, Cogun, Can and Gul Tosun. A study on kerf and material removal rate in wire electrical discharge machining based on Taguchi method, Journal of Material Processing Technology. 152, pp.316-322. 2004.

Uhlmann, E., Piltz, S. and S. Jerzembeck. Micro-machining of cylindrical parts by electrical discharge grinding, Journal of Materials Processing Technology. 160, pp.15–23. 2005.

Van Dijck, F., 1973. Physico-mathematical analysis of the electro-discharge machining process, Dissertation, Katholieke Universiteti Leuven, Leuven, Belgium. 1973.

W. Koenig, Fertigungsverfahren Band 3: Abtragen, VDI Verlag GmbH, Duesseldorf, 1990.

Wang, W.M., Rajurkar, K.P., and S. Boyina.Effect of the thermal load on wire rupture in WEDM, Transactions of NAMRI/SME 20, pp.139–144. 1992.

Watanabe, T. Sato, and I. Suzuki. WEDM monitoring with a statistical pulse-classification method, Ann. CIRP, 39 (1), pp. 175-178. 1990.

Weck, M., Fischer, S. and M. Vos. Fabrication of micro components using ultra precision machine tools, Nanotechnology, 8, pp.145–148. 1997.

Weng, Feng-Tsai, Shyu, R. F. and Chen-Siang Hsu. Fabrication of micro-electrodes by multi-EDM grinding process. Journal of Materials Processing Technology. vol. 140, pp. 132-334. 2003.

Weng, Feng-Tsai, Shyu, R. F. and Chen-Siang Hsu. Fabrication of micro-electrodes by multi-EDM grinding process. Journal of Materials Processing Technology. vol. 140, pp. 132-334. 2003.

Weng, Feng-Tsai, Shyu, R. F. and Hsu, Chen-Siang. Fabrication of micro-electrodes by multi-EDM grinding process. Journal of Materials Processing Technology, 140, pp.332-224. 2003.

Y. S. Liao and Y. P. Yu. Study of specific discharge energy in WEDM and its application, International Journal of Machine Tools and Manufacture, 44, pp.1373-1380. 2004.

Yan, Biing Hwa, Tsai, Hsien Chung, Huang, Fuang Yuan, Lee, Long Chorng. Examination of wire electrical discharge machining of Al2O3 p/6061 Al Composites, International Journal of Machine Tools & Manufacture, 45, pp.251-259. 2005.

Yan, Mu-Tian, Huang, Chen-Wei, Fang,Chi-Cheng and Chia-Xuan Chang. Development of a prototype Micro-Wire-EDM machine, Journal of Materials Processing Technology. 149, pg. 99-105. 2004.

Zhang, J., Huang, C. Y. and C. Y. Yue, Study on the sign of wire breakage in WEDM-HS, ISEM 10, pp.304-307. 1992.

PUBLICATION LIST

International Journal

[1] Alam, S. M., Rahman, M. and H. S. Lim. **Study of WEDM Parameter Phenomena for Micro-Fabrication**, International Journal of Manufacturing Technology and Management, Special Issue on Micro-Fabrication *(accepted for publication)*

International Conference

[2] Alam, S. M., Rahman, M. and H. S. Lim. **Wire EDM technology with a focus on enhanced micro precision fabrication**. Published in the Proceedings of the 6th European Society for Precision Engineering and Nanotechnology (Euspen) International Conference, 28 June - 1 May 2006, Baden bei Wien, Vienna

[3] Alam, S. M., Lim, H. S. and M. Rahman. **Development and Evaluation of a Micro Wire EDM Device** International Conference on MEMS and Nanotechnology (ICMN '06), 14-15 March, 2006, Kuala Lumpur, Malaysia

[4] Alam, S. M., Rahman, M and H. S. Lim. **Microstructure study of the effect of Wire EDM on Silicon** 2nd MRS-S Conference on Advanced Materials, organized by Materials Research Society (poster presentation), Singapore and Institute of Materials Research and Engineering. 18-20 January, 2006, Singapore

[5] Alam, S. M., Rahman, M and H. S. Lim. **Experimental investigation of the effects of control parameter on machining characteristics in Wire EDM.** Paper submitted for 7th Asia Pacific Conference on Material Processing (APCMP), 4 – 6th December, 2006, Singapore

APPENDIX A

DETAILED DRAWINGS OF MICRO-WEDM DEVICE

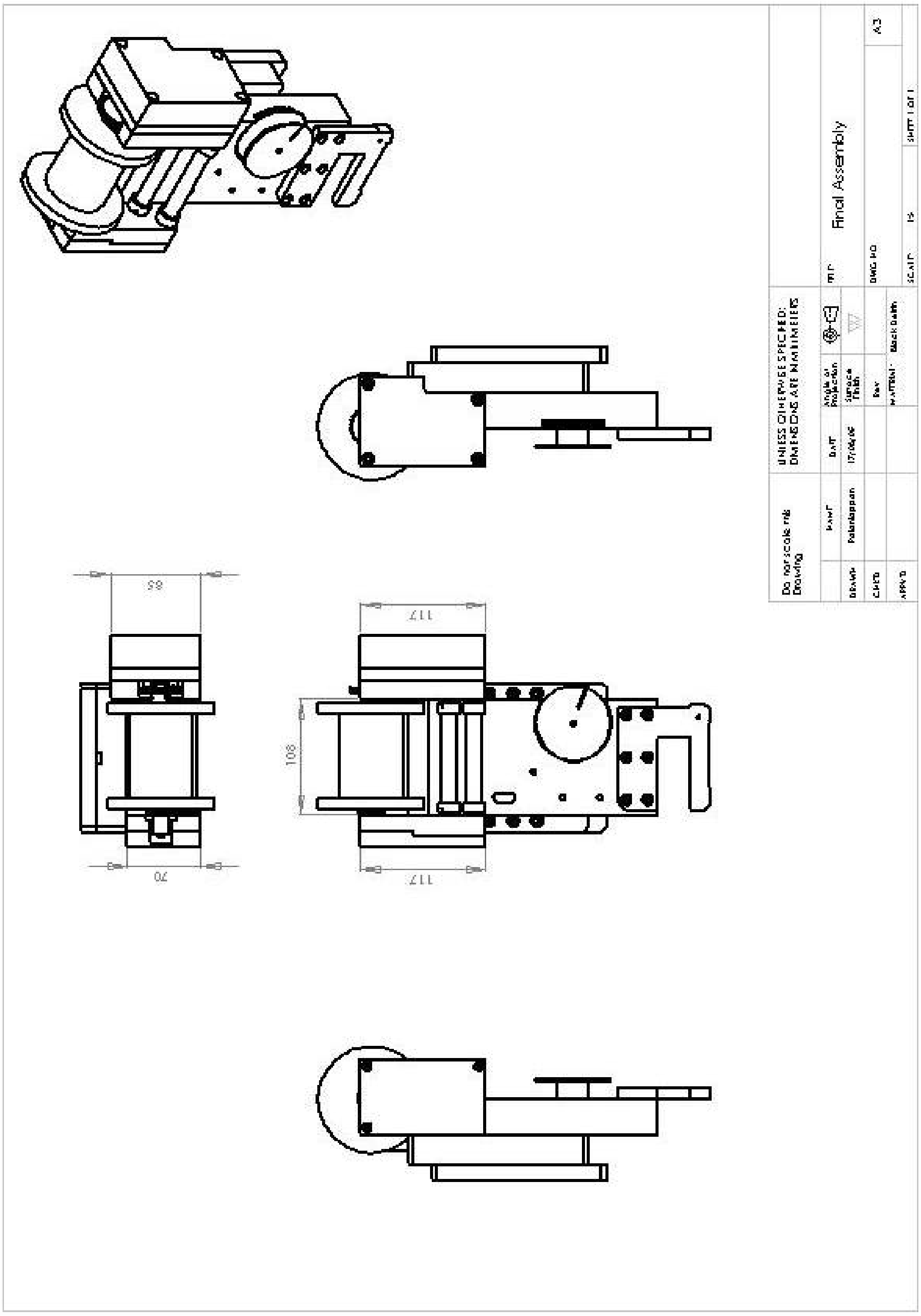


Fig A.1: Final Assembly

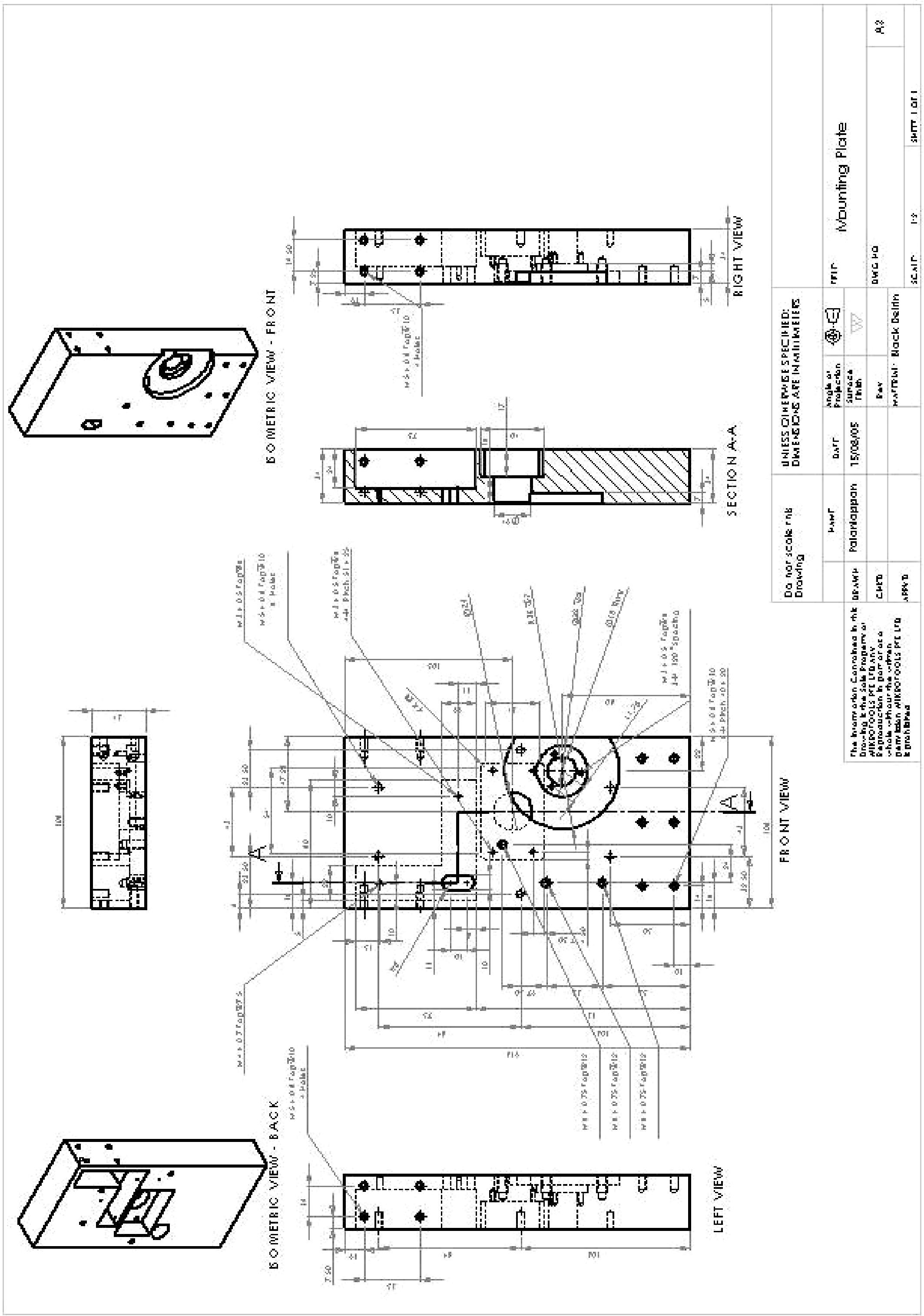


Fig A.2: Mounting Plate

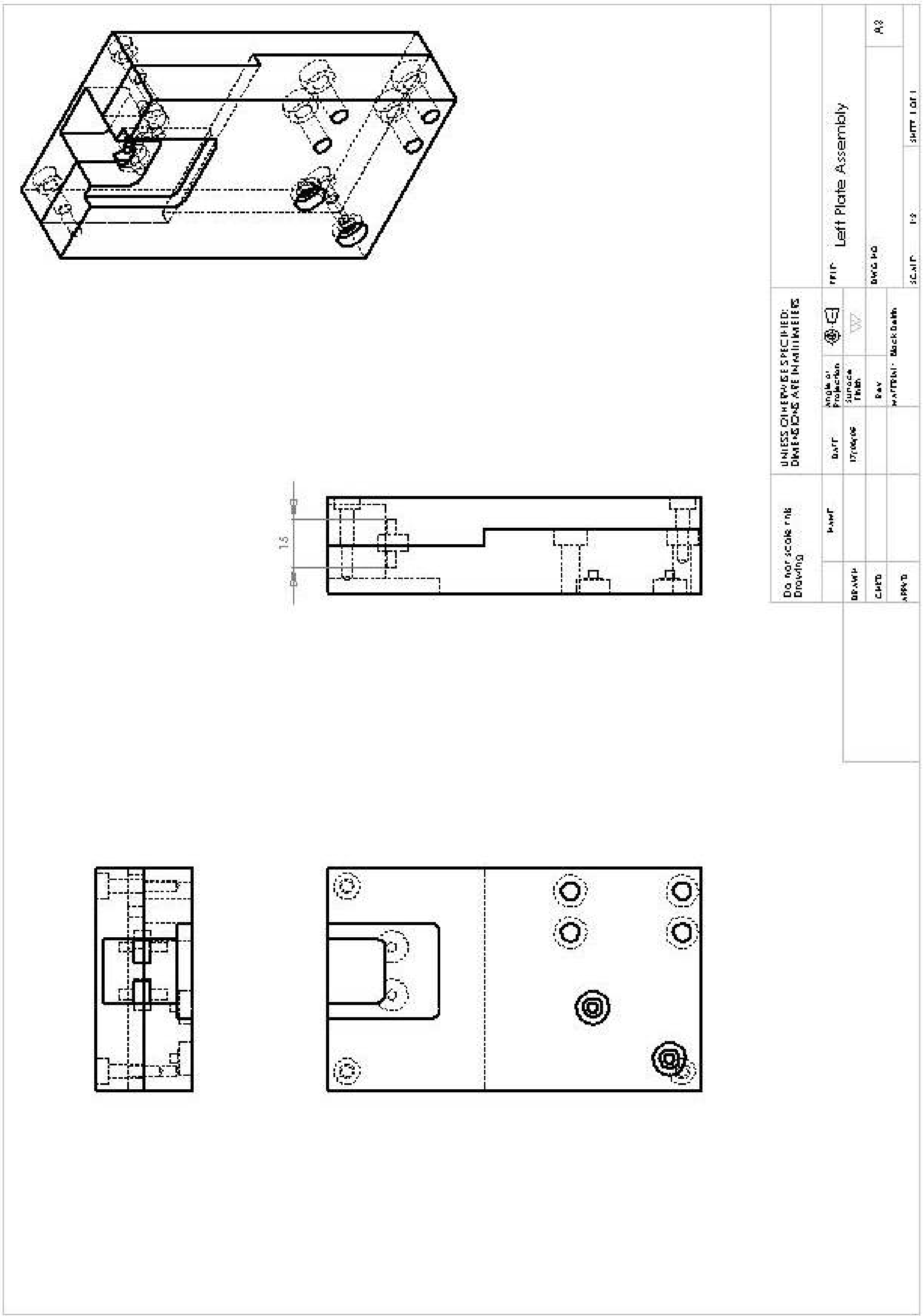


Fig A.3: Left Plate

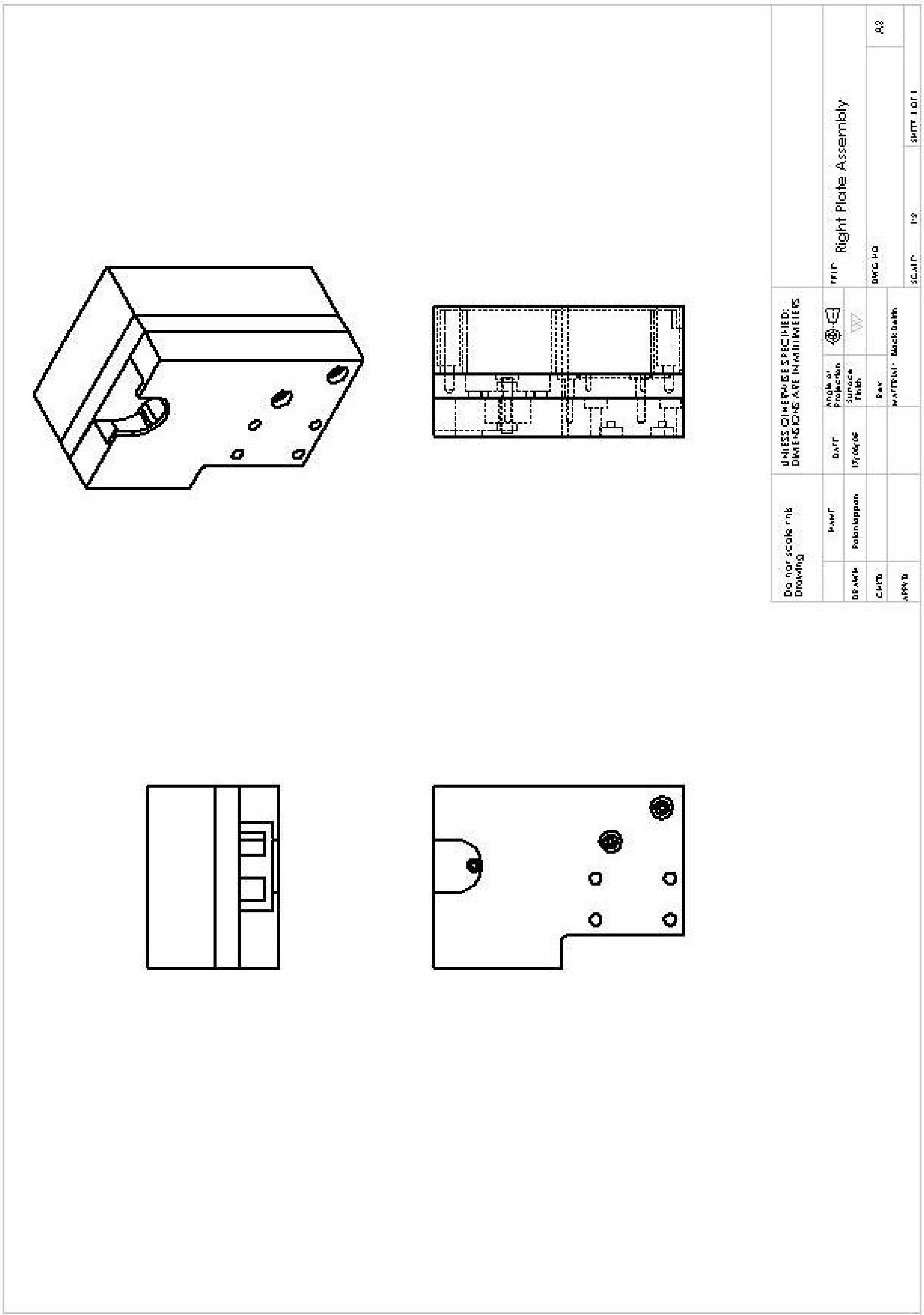


Fig A.4: Right Plate

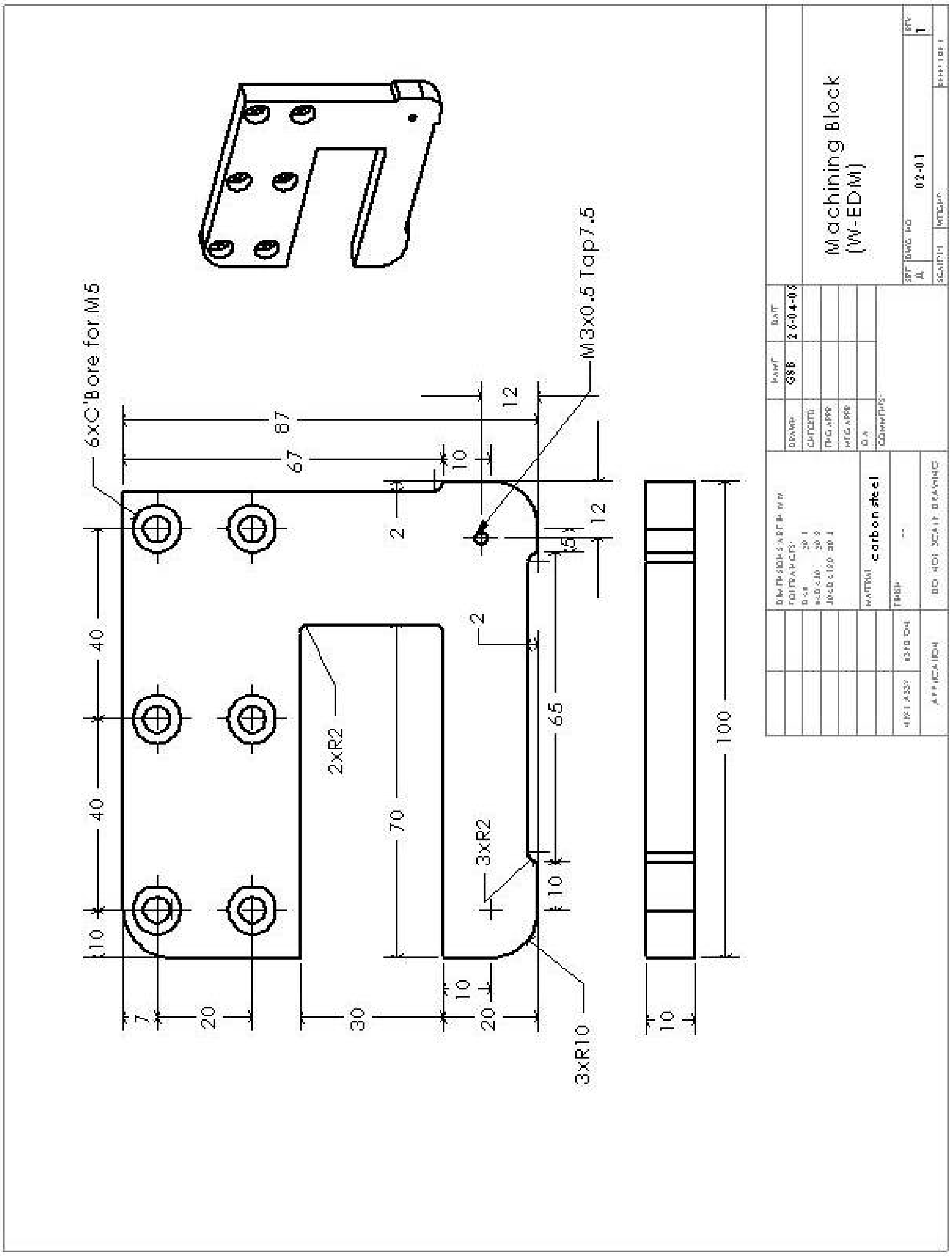


Fig A.5: Machining Block

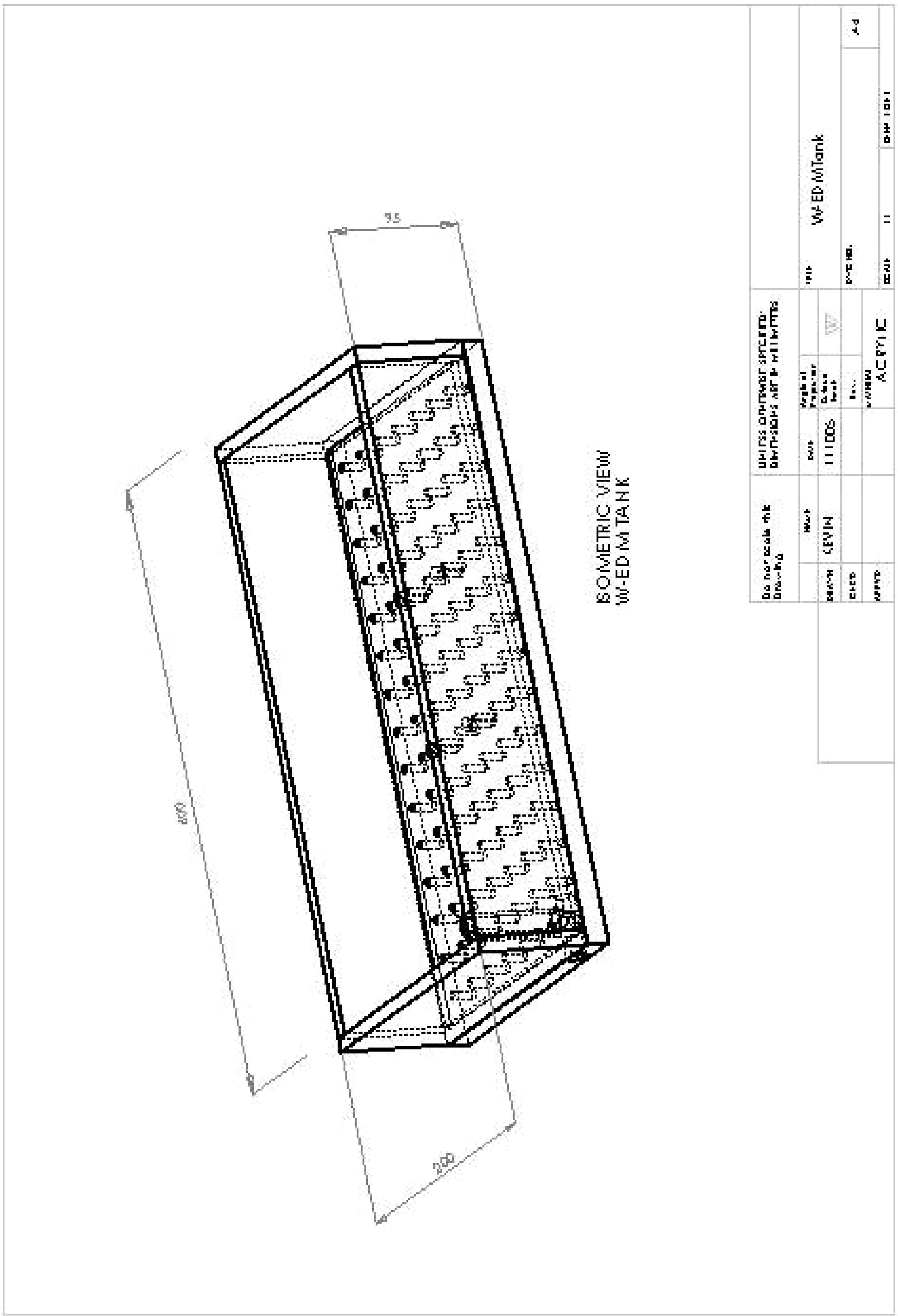


Fig A.6: Wire EDM Tank, isometric view

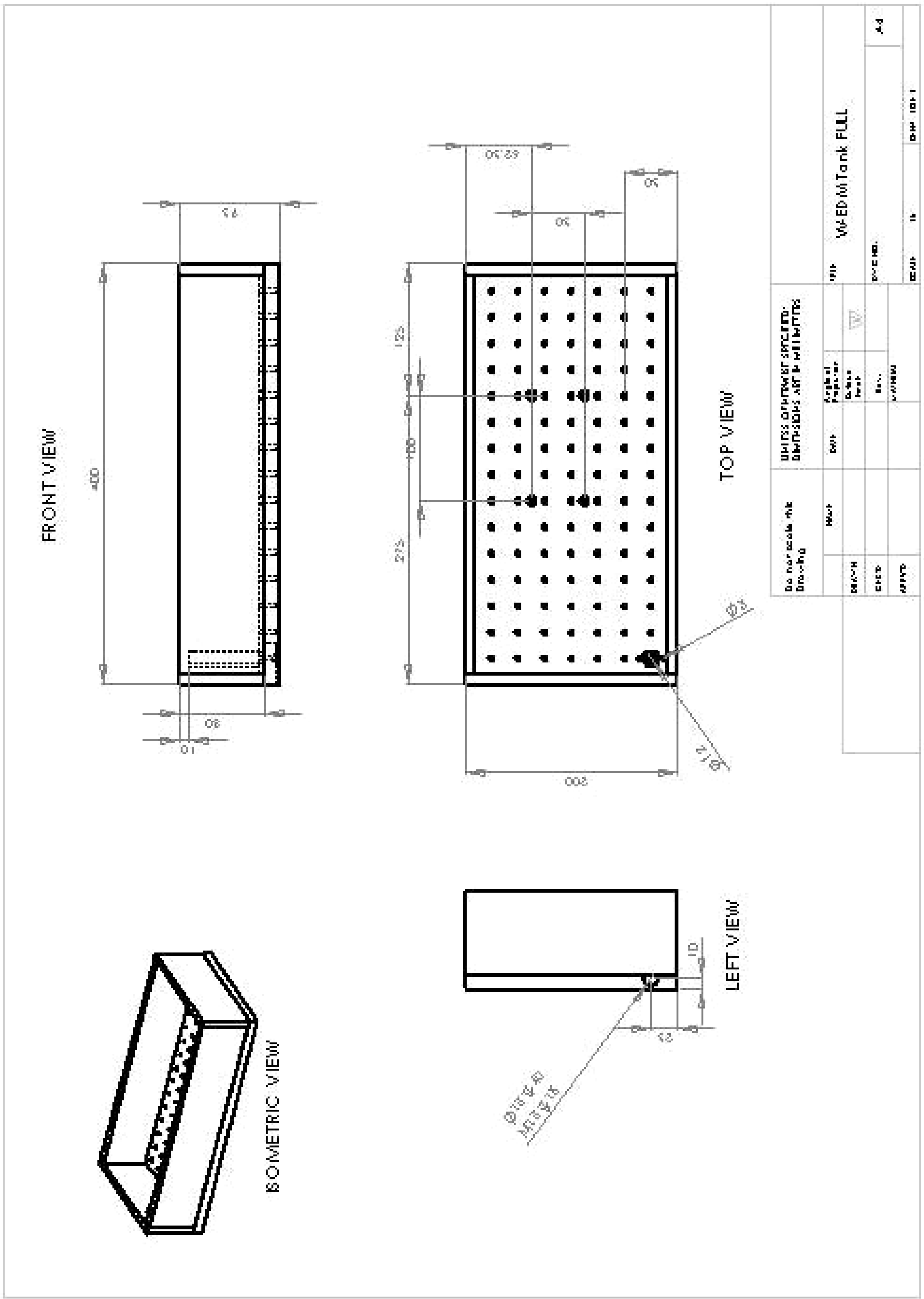


Fig A.7: Wire EDM Tank, front and side view

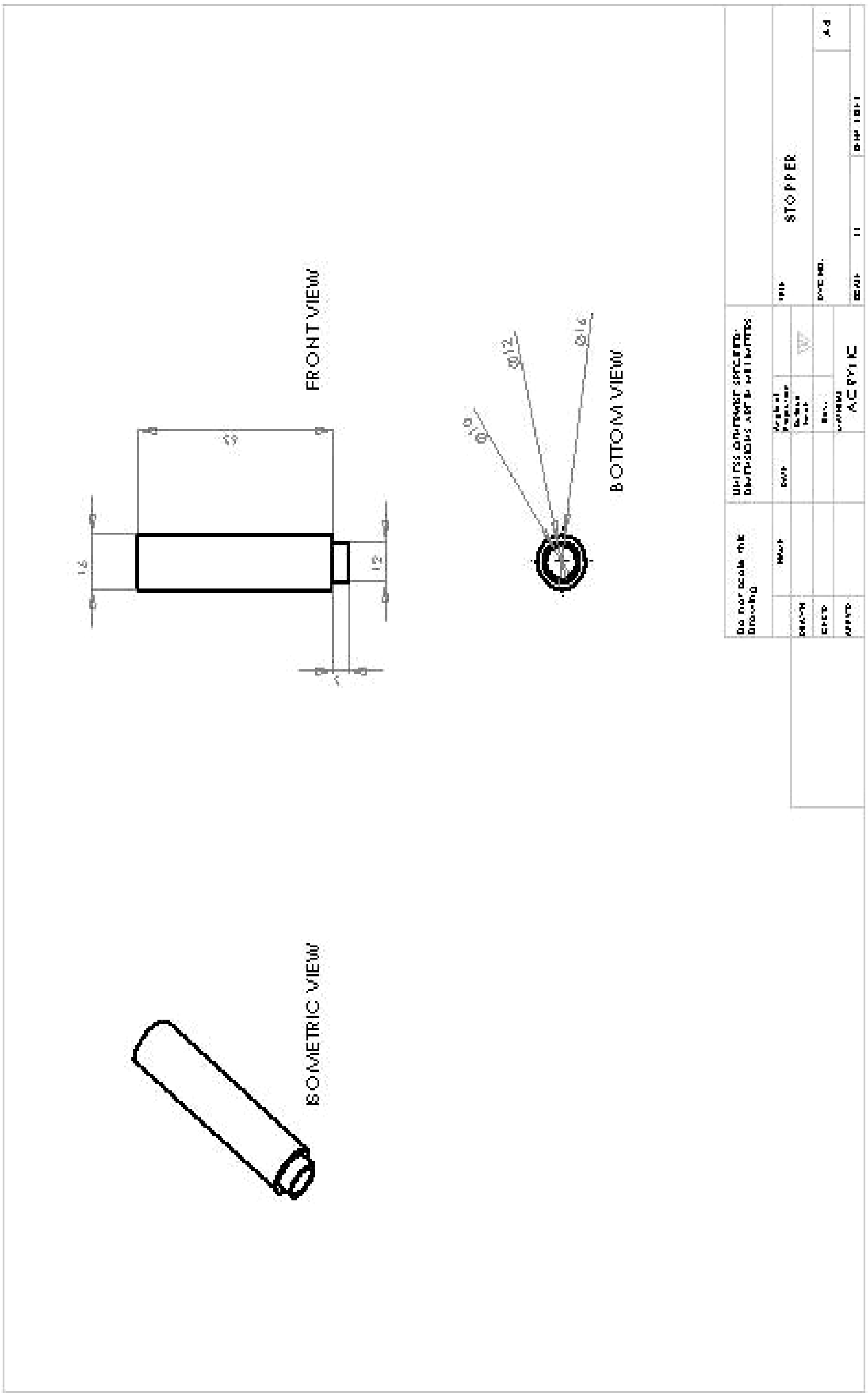


Fig A.8: Stopper

APPENDIX B

WIRE TENSION CALIBRATION

B.1 Determining the tension value for WEDM

The values of the tension of the wire are investigated, since only percentages are shown in the display of the WEDM platform. To calculate the actual tension in the wire, there is a need to find the spring constant of the spring.

The spring constant of the wire was determined by using a micrometer gauge known as the microsensor. The spring is placed in the holder of the machine, and successive known loads are applied to the spring. The subsequent extensions of the spring were taken down and plotted on a graph. The spring constant is found by taking down the value of the gradient, as shown in graph 1. From the gradient of the line, the value of the spring constant was found to be 0.0103.

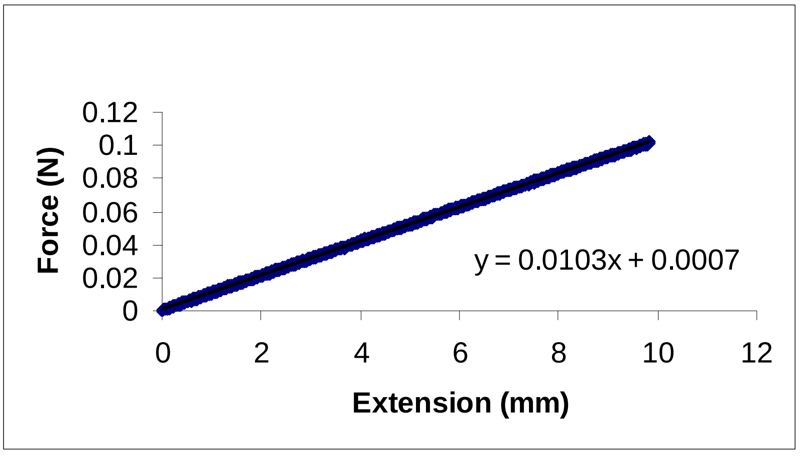


Figure F.1: Graph of Force (N) vs Extension (mm)

B.2 Calculatiion of tension values

To find the actual value of the tension, the extension (excluding the original length of the spring) of the wire was taken down with every increment of the percentage of the tension value. Using Hooke's law, the tension value was calculated. The results are shown in table F.1:

Sample Calculation:

For 15% tension value,

Force = spring constant * extension

= 0.0103 * 17.70

= 0.18231 N

Table F.1: corresponding tension values to percentage values of tension

	Spring Constant		0.0103	N/mm		F = K * E
	Original spring length		18.4	mm		
No	*Tension (%)*	*Tension (N)*	*Length (mm)*			
			1st reading	*2nd reading*	*Average*	*Extension (mm)*
1	5	0.16841	34.50	35.00	34.75	16.35
2	10	0.17768	35.50	35.80	35.65	17.25
3	15	0.18231	36.00	36.20	36.10	17.70
4	20	0.18489	36.20	36.50	36.35	17.95
5	25	0.18952	36.80	36.80	36.80	18.40
6	30	0.19261	37.00	37.20	37.10	18.70
7	35	0.19519	37.20	37.50	37.35	18.95
8	40	0.19931	37.50	38.00	37.75	19.35
9	45	0.20291	38.00	38.20	38.10	19.70
10	50	0.20652	38.40	38.50	38.45	20.05

APPENDIX C

WIRE SPEED CALIBRATION

C.1 Determining the rpm value of electrode wire

In the CNC program the software interface has the option to select the wire speed in terms of %. According to the % value set, the current supplied to d.c. stepper motor responsible for wire speed control is changed. This in response controls the motor speed. In order to convert the % values to rpm, speed calibration experiments were conducted.

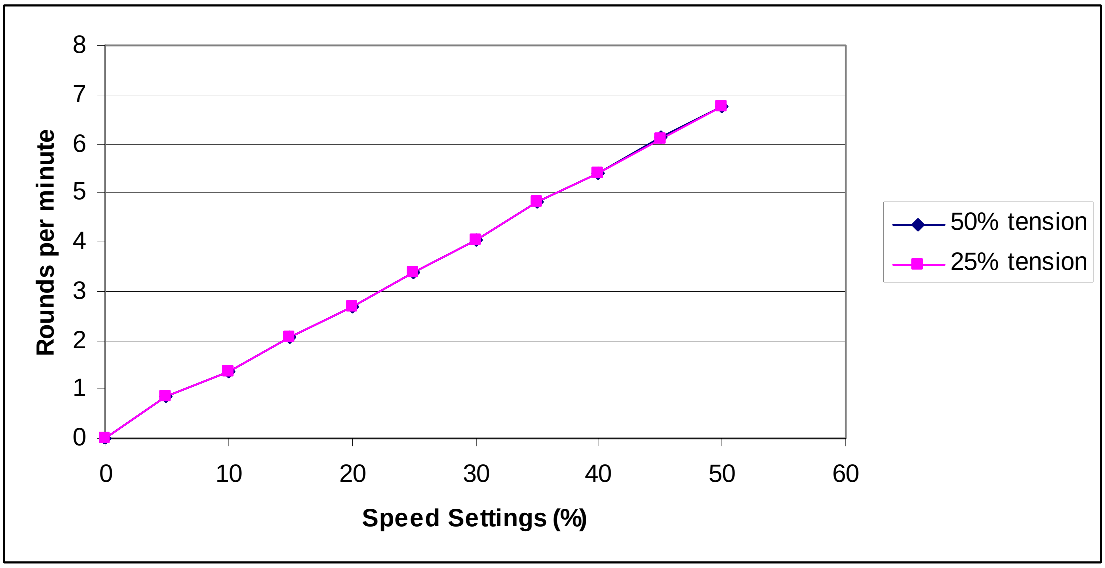


Figure C.1: Relationship between the speed setting and corresponding rpm values

The experiments were conducted at two different tensions setting (at 25% and 50%) to take into account if there is any variation in wire speed due to tension. But it was evident from the graphs that the trend is quite similar and the tension setting doesn't have effect on wire speed.

The experimental result (numerical data are included in Appendix C) demonstrate that the minimum wire speed is 0.87 revolution per minute (rpm) corresponding to 5% setting and maximum is 6.74 rpm corresponding to 50% setting. Although the rpm value seems small, but since the machining is essentially a micro-machining, thus very thin work piece are machined. For such micro-machining higher speed is not necessary.

C.2 Wire Material Consumption

Based on the wire rpm, the estimated wire consumption is found out (table C.1). At 5% speed setting on an average per minute approximately 82 mm of wire is consumed. At 50% speed the wire consumption is about 635 mm per minute.

Table C.1: Data on wire material consumption

Diameter of collector reel = 30 mm
Perimeter = 94.24778

Speed Setting	Average Rpm	Wire consumption
%	rpm	mm/min
0	0.0	0
5	0.87	81.99576
10	1.345	126.76356
15	2.04	192.26592
20	2.69	253.52712
25	3.365	317.14452
30	4.04	380.76192
35	4.81	453.33288
40	5.395	508.46796
45	6.105	575.38404
50	6.74	635.23152

APPENDIX D

EXPERIMENTAL INVESTIGATION OF WEDM ON SILICON

D.1 Introduction

The monocrystalline silicon is a very important material from its application point of view, especially in the field of microelectronics. To enhance the practical applications, fabrication in the micron level is of great importance and also the post-process phenomena at the microstructure level are necessary to understand. μWEDM is now an accepted machining process that has great potential for micro-fabrication. Both in the theoretical and practical arena, there have been only a limited number of studies on the implication of EDM on silicon. Especially there is even little work on the application of WEDM on silicon material. As part of this research work, the possibility to fabricate micro-components on silicon material with WEDM technique has been examined. At the same time how the process impact the material after machining has been carefully observed. The process effect on the microstructure of silicon was examined with the help of high-resolution microscope and scanning electron microscope. As a practical application, attempts have been taken to fabricate a micro-spring made of monocrystalline silicon. Such spring can find its application in micro-mirrors, sensor and other microelectrocmechanical systems.

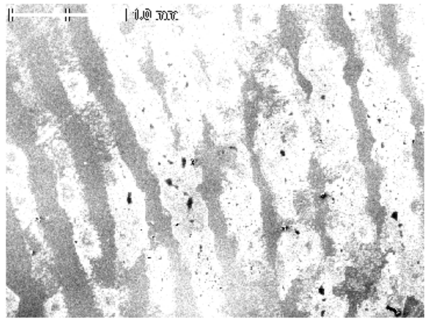
Already WEDM has been adopted as a new candidate for silicon slicing [Peng and Liao, 2003]. When compared with other existing method such as inner diameter saws or wire saws to slice silicon ingots, it is found that WEDM has some important advantages and good results.

For EDM operation on Silicon the main challenge lies in the fact that Silicon is semi-conductor. But if the resistance can be decreased EDM can be applied to silicon which has good prospect in practical area. In the literature review chapter, previous attempts for the application of WEDM on silicon are mentioned. Please refer to chapter 2, section 2.3.11, titled Application of WEDM for micro-fabrication.

D.2 Improving EDM efficiencies of silicon through ohmic contact

One of the major challenges for machining semiconductor materials is the resistivity, since conductance between the workpiece and the electrode is very essential. Kunieda and Ojima (2000) have demonstrated that single silicon crystal can be improved by reducing the contact resistance between the silicon single crystal and metal electrode. To decrease the contact resistance, the rectifying contact between the silicon wafer and metal was changed into an ohmic contact. In the case of p-type silicon, the contact surface of the silicon wafer was plated with aluminium by vaccum evaporation and aluminium was doped into silicon by diffusion process.

For n type silicon, Sb-Au was used in place of Al. Experimental results show that machining rate can be improved dramatically by changing the rectifying contact into an ohmic one.



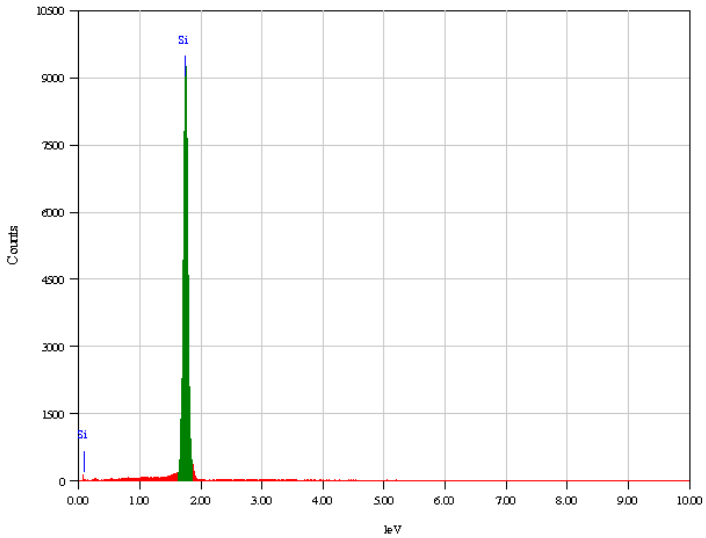


Figure D.1: The EDX analysis of the silicon workpiece

D.3 Integrating EDM and photolithography techniques

One of the disadvantages of photolithography techniques to machine silicon is the fact that they are essentially 2.5D processes. EDM does not have this limitation: it allows complete freedom in the shapes that can be made. Thus truly remarkable three dimensional structures can be fabricated by WEDM techniques.

This would enable the integration of lithographic techniques and EDM for the manufacture of complex microsystems. In this view, EDM would be used to machine the mechanical structure of microsystem, thus benefiting from its versatility; while lithographic techniques can be use for providing local intelligence, i.e. Integrated Circuits on the microstructures. This combination would open up a whole new field of complex microstructures, which are still relatively easy to design and manufacture.

D.4 Possible Area of Application

- Microfabrication of MEMS
- Integrating photolithography with EDM
- Alternative to conventional micromachining of silicon

D.5 Experimental Methods

During the study a series of experiments on silicon was conducted. The experiments were conducted with tungsten wire of diameter 70 and 50 micron. Deionized water was used as dielectric fluid.

Monocrystalline silicon was selected as working material. The characteristics of the material are:

- Type: p,
- Orientation: 111,
- Resistance: less than 1 (one) ohm,
- Thickness: 500 to 800 micron,
- Surface: P1S.

Some major parameters that influence machining characteristics in WEDM, such as open voltage, peak current, spark on time were used to evaluate the effect. After machining microstructure study was conducted to investigate the effect of WEDM on silicon. Keyence Digital Microscope and Scanning Electron Microscope was used for microstructure study.

D.6 Experimental Results

Mostly the surface profile, the micro-structure of the surface, the gap width feature, edge craters are observed. In figure D.2 the surface profile of the WDEMed surface is observed. From the measured values it was found that the maximum peak of the surface roughness was 0.29 micron meter and the average was about 0.15 micron meter. Parameters used to cut the silicon are given in table D.1.

Table D.1

Volt	Resistance	T_{on} / T_{off}	Wire Ten.	Wire Speed	EDM speed
75 volt	33 ohm	15 μs / 15 μs	30%	30%	10 μ/s

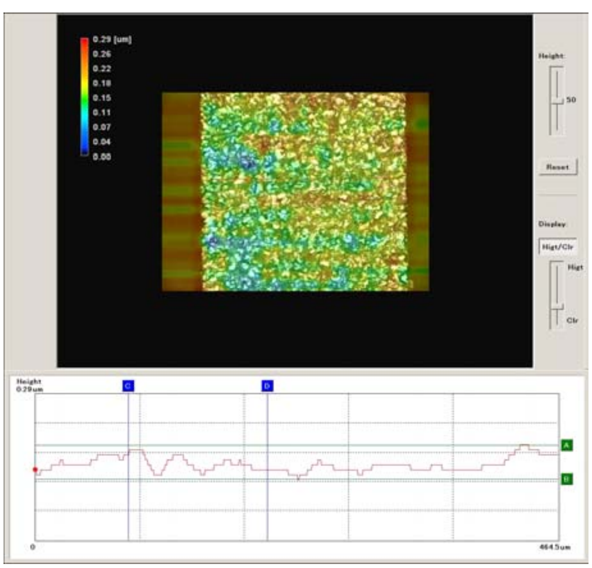


Figure D.2: The surface profile

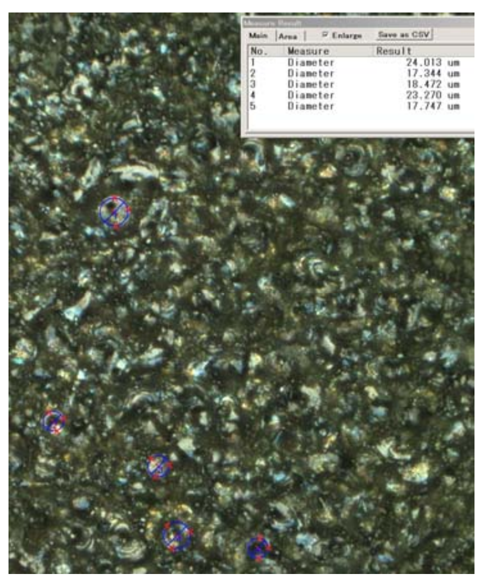


Figure D.3: WEDM Crater on surface

During the electrical discharge during machining, craters are produced on the surface. The craters were studied in the figure D.3. The size of the craters produced on the surface varied from 17 micron meter to 24 micron.

In figure D.4 the close-up image of the gap width is given. Since the spark energy was high it is obvious that the edges of the gap width are quite rough. Such high energy should be employed only for rough cutting where achieving higher machining rate is the main target than better surface roughness. The edge of the part cut is shown in figure D.5.

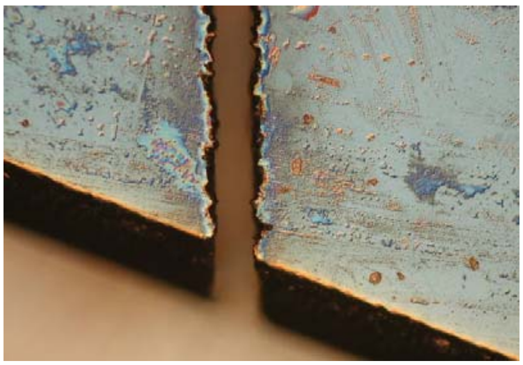


Figure D.4: Gap width feature. 25X magnification

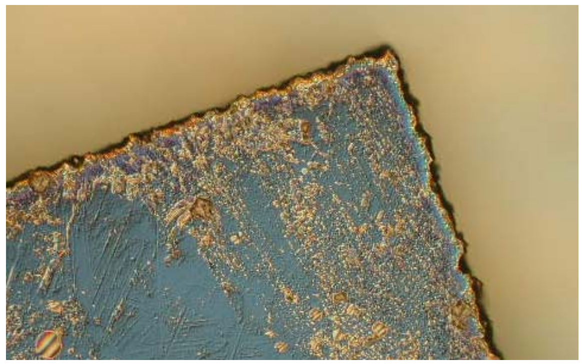


Figure D.5: Edge of silicon after WEDM operation. 25X magnification

In figure D.6 the edges of the surface produced by WEDM is measured. From the measured values it was found that the diameters of the craters are quite random. Not all of them are of same size. It shows the stochastic nature of the sparking phenomena of WEDM technology.

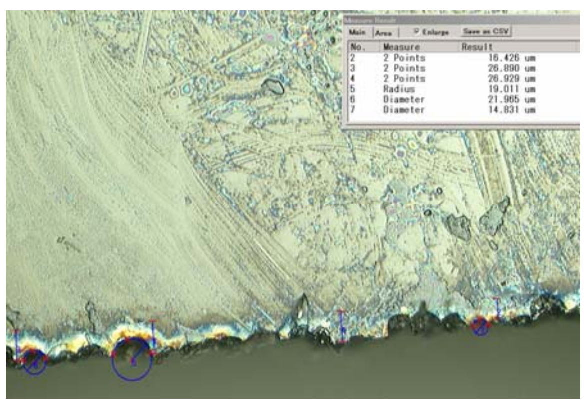


Figure D.6: Edge of silicon after WEDM operation. 25X magnification

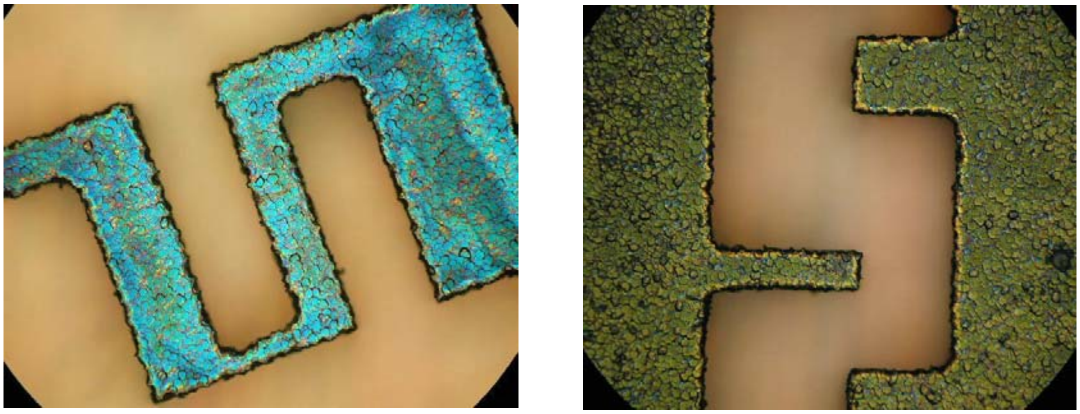


Figure D.7: Example of WEDM spring manufactured on silicon. Magnification 30X

D.7 Results

For precision machining, obtaining very minimum gap width is very important. From experimental study it is found that gap voltage (V), current (I) and spark on time (Ton) are the most important parameter that determine the gap width.

From the experimental results it is evident that silicon material can very well be machined and fabricated using WEDM technology. The semi-conductive property of the silicon does not put any barrier in such process. The Impact of WEDM on the material shows that the control of parameter is very important. As a material, silicon is very much less dense than metals, the parameter to be used need to be much moderate to minimize surface damage. The attempt to fabricate a micro-spring was successful to some extend. An unfinished attempt to manufacture micro spring from silicon is demonstrated in figure D.7. Further study need to be completed before such micro-spring can be put into real application.

It seems that since very thin silicon workpieces are used, so the intensity of the spark needs to be reduced to as low as possible. Thus a recommended parameter value would be a voltage below 50 volt, resistance of 100 ohm and spark on time below 10 micron second.

There were some practical problems encountered when machining Silicon Wafer and need to be taken care of, such as:

- Excessive Brittleness of Silicon wafer requires extra caution while mounting the workpiece as well as for post operation handling.
- Contamination should be avoided.
- Thermal treatment may be required to restore the crystallographic structure of silicon wafer after WEDM operation.

APPENDIX E

STUDY ON CONTROL PARAMETERS: SHORT AND OPEN

E.1 Introduction

Control parameters are mostly neglected as study parameter to understand their effect on machining characteristics. There is not much study to establish whether the control parameters are also influential along with established cutting parameters such as spark on time, voltage, current, wire tension etc. In this chapter two control parameter of the WEDM machine – Short detection and open were studied on machining characteristics such as gap width, material removal rate (MRR) and machining time.

E.2 Short Detection Parameter

Experimental investigation was conducted during the research about the effects of control parameter on machining characteristics in WEDM. The ‘short detection’ parameter was incorporated in the newly developed WEDM machine. The parameter was incorporated primarily for control purpose and fine tuning the electro-discharge behavior. The parameter ‘Short’ in the CNC program is a parameter to determine how many continuous sparks will be considered as short circuit. It is primarily a control parameter. Up to the knowledge of the authors from the literature investigations it reveals that the published work available do not provide any specific information on the control parameter, short detection and its effect on machining characteristics.

From the basic understanding of the spark phenomena in electro-discharge machining it is reasonable that short detection parameter has it's implications for the machining result. This is explained below:

- When short parameter is set to high value, there will be more continuous sparks before the discharge circuit is turned off. Thus a large value is helpful to machine faster.
- Because of less successive sparks, a smaller value is helpful for better machining surface, So crater generated will be less intensive, which translates to better surface.
- But too large will mean faster machining but bad machining surface.
- Too smaller means better surface but too long machining time.

In WEDM operation, the control algorithm for determining when there will be discharge and electrode retraction due to short circuit - depends on the 'short detection' parameter. The control algorithm is described below:

a. As the execution of the WEDM starts, power supply turn on, the wire starts running and continues to move towards the workpiece.
b. Once the gap between the wire and workpiece is very small, spark occurs.
c. During the spark the applied voltage between the electrode and the workpiece is reduced. There is a threshold voltage level set for each setting of open voltage. With the help of a threshold voltage setting, sparks are detected and counted.
d. If the voltage drop is below threshold (with the help of a voltage comparator), it is considered as proper machining spark and servo motor motion status is set to HOLD.

e. When the number of continuous sparks exceeds ‘short’ parameter set in the software, the condition is set as short. When it is short circuit condition, a retract signal is sent and the electrode is retracted by the time set by the ‘Open’ parameter. It is equivalent to the number of one complete cycle consisting of set T_{on} and T_{off}.
f. In case when the number of continuous sparks don’t exceed ‘short’ sparking continues.
g. When normal discharge occurs, the machine continues with HOLD status. The wire doesn’t advance. After some time materials ahead of electrode erode, gap is widened and no spark occurs.
h. Voltage again jumps over threshold.
i. Electrode is advanced and from new spark the count of sparks is reset from 1.

So, in determining the number of continuous sparks, the short detection parameter plays a pivotal role. Since the surface characteristics are very much determined by the pattern of sparks, therefore the short detection parameter’s effect on WEDM is worth exploring.

In this study, the machining characteristic factors studied were gap width or kerf, MRR and machining time. Mostly the short detection parameter was changed while keeping other parameter constant. Also different voltage and current setting was used to compare different set of data. The MRR was calculated in terms of square area. For measuring gap width or kerf, slots were cut on workpiece and later the gap widths were measured using digital microscope.

E.3 Effect on gap with

The effect of short parameter on gap width is shown in figure I.1. In this graph the data are calculated for gap voltage of 150 (peak current 4.545 amp) and 75 volt (peak current 2.272 amp). Other constant parameters were, pulse on time 9 μs and pulse off time 12 μs, EDM speed 20 μ/s, Wire run speed 8.45 mm/sec, wire tension 40%.

Table E.1: Fixed parameters

Wire Speed	*Wire Tension*	*Ton, Toff μs*	*Volt*	*Res. Ω*	*EDM Speed μ/s*	*Open*
40%	40%	9, 12	150, 75	33	20	5

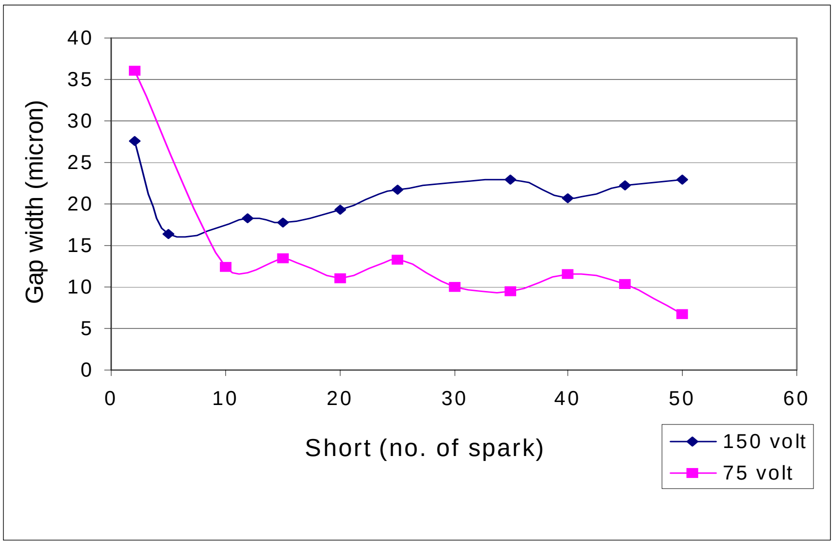


Figure I.1: Effect of short detection parameter on gap width

At higher voltage, the gap widths keep increasing with increasing 'short' parameter. The better gap width (lower the better) was obtained at lower value of short. At lower voltage the gap widths remain almost same for most of the part showing a slight opposite trends, i.e. higher 'short' value yielded better gap width. When current intensity is high, the machining characteristics are heavily influenced with short parameter, since it determines the number of successive sparks. As the peak current is high, so increasing short parameter leads to higher material removal, and thus gap width continues to increase.

The short parameter seems to have lesser effect on the gap width when the voltage is 75 as compared to 150. Short parameter of value from 10 to 45 yield almost similar results. This can be explained by the fact that in case of 75 volt, the intensity is very low. Thus the effect of short parameter is diminished to a great extent. The gap width keep fluctuating because at lower voltage and current, other factors such as flushing condition, pulse on time etc. dominate the machining condition more.

But interestingly at the lowest value for both voltage levels, the gap width is not the best as it might be expected. The optimum gap width for 150 volt was in the range of 5 to 7. For 75 volt, the optimum value was 35 and 50.

E.4 Effect on material removal rate

The effect of short parameter on MRR is demonstrated in figure I.2. The trend shows that increasing the 'short' parameter increase MRR more or less consistently throughout the range, with only few minor fluctuations. The values of the constant parameters are mentioned in the graph.

Table E.2: Fixed parameters

Wire Speed	*Wire Tension*	*Ton, Toff* μs	*Volt*	*Res.* Ω	*EDM Speed* μ/s	*Open*
40%	40%	27, 36	150	33	20	5

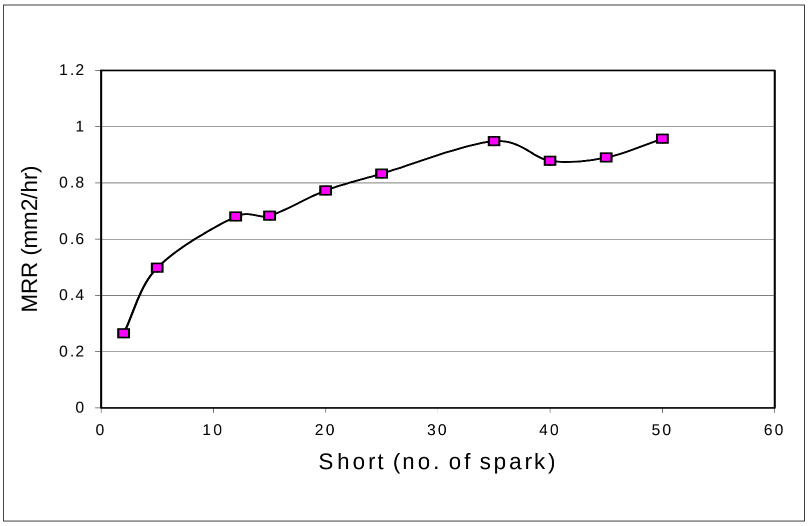


Figure E.2: Effect of short detection parameter on material removal rate

The analysis of the results indicates that higher 'short' parameter exhibit better performance with regard to MRR. This suggests that when higher MRR is needed, the short parameter should be set at higher value. The prime reason behind getting a higher MRR with high short value is because when short is set at high, the machining continues and ignores short-circuiting conditions. At low short value short circuit is detected frequently, thus the wire electrode retracts and machining is interrupted more often. This takes more time to finish machining a particular area and causes a lower MRR.

E.5 Effect on machining time

The effect on machining time has been demonstrated in figure I.3. The time to machine seems to stabilize after certain value (in this case at 12). So increasing short parameter doesn't improve much the time to machine. But it is of importance to notice that even though the machining time doesn't change even at higher 'short' value, but the MRR (as evident from figure E.2).

Table I.3: Fixed parameters

Wire Speed	*Wire Tension*	*Ton, Toff µs*	*Volt*	*Res. Ω*	*EDM Speed*	*Open*
40%	40%	27, 36	150	33	20 µ/s	5

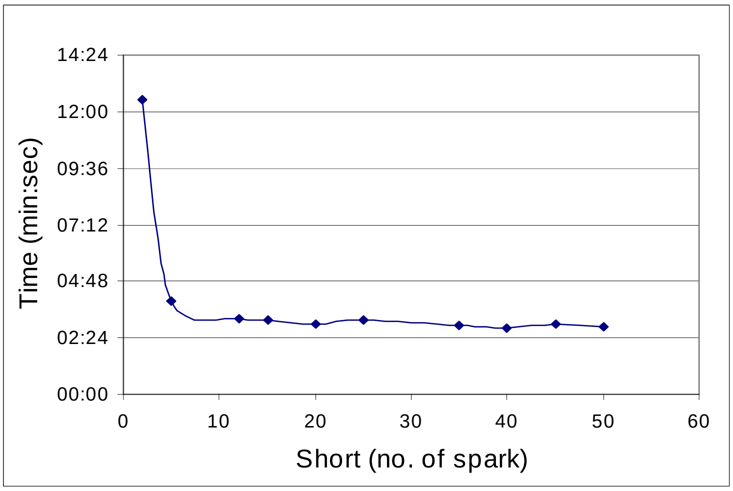


Figure E.3. Effect of Short detection parameter on machining time

This signifies that there is an undesirable machining effect (excessive material removal) when short parameter is increased at further higher value. Since machining time doesn't improve after a short value of 10 or so, it is recommended that even when faster machining is desired (as for rough cut), the short parameter need not to be increased too high. The minimum machining time was obtained between 20 to 40 of short value. A short parameter between 5 to 10 would also suit the purpose fairly. Setting the short parameter too high would only lead to undesirable widening of kerf or gap width.

Thus for finer machining, a short parameter of value between 5 to 10 is recommended, which would ensure better gap width as well as reasonable machining time. For rough cut short parameter can be set between 20 to 40 depending on the higher or lower MRR requirement.

E.6 Results of short detection

Summarizing the main features of the results, the following conclusions can be drawn about the short detection parameter:

1. The short parameter has observable effect on gap width. It is more profound at higher voltage. When the gap voltage is high, current intensity goes high which cause short parameter to influence more on the gap width.
2. For better (lower) gap width, short parameter should be set low. 'How does short parameter behave at lower voltage' still demand further investigation. From the experimental trends it seems at lower voltage and current intensity the effect of short parameter diminishes.
3. For higher MRR, higher setting of short parameter is ideal.
4. Although MRR goes on increasing with higher short parameter setting, machining time remains almost the same after certain limit. There is an undesirable excessive material removal effect when short parameter is too high.

The study demonstrates that the short detection parameter has significant effect on machining characteristics in terms of gap width, MRR and machining time. This also implies that for fine tuning the control of the WEDM process, short detection parameter along side other well established parameters, needs to be given due consideration.

E.7 Open Parameter

The open parameter can be defined as the amount of time the electrode retracts once a short condition is identified. It depends on the total cycle (on plus off time). For illustration purpose lets say T_{on} is 5 μs and T_{off} is 10 μs, then total cycle time is 15 μs. Now if the open parameter is say, 4. That mean once the machining condition is short, the electrode will retract for a time of 4 times 15, which is 60 μs.

From the above illustration it is clear that Open parameter is mostly related to the machining time, i.e. MRR. So a higher open parameter may lead to higher machining time. It is worth noticing that the influence of open parameter only comes into play when there is short circuit condition. Thus the short parameter which determines when and how short circuit is identified, also has its own influence on open parameter. From experimental study it was verified.

E.8 Effect on Material Removal Rate and Machining Time

From the machining control panel open parameter value was changed from 5 to 50 with an increase of 5. During machining required time to machine fixed amount of programmed path was calculated. Also the gap width was measured to see if there is any influence on it. The fixed parameters used in the experiments were: 100 volt, 33 ohm, both T_{on} and T_{off} 10 μs.

Table I.4: Fixed Parameters

Wire Speed	*Wire Tension*	*Ton, Toff μs*	*Volt*	*Res. Ω*	*EDM Speed μ/s*	*Short*
40%	40%	30, 60	100	33	20	10

Material : Stainless steel (finest tempered), thickness 0.20 mm
Electrode : Tungsten wire, diameter 70 micron (0.07 mm)

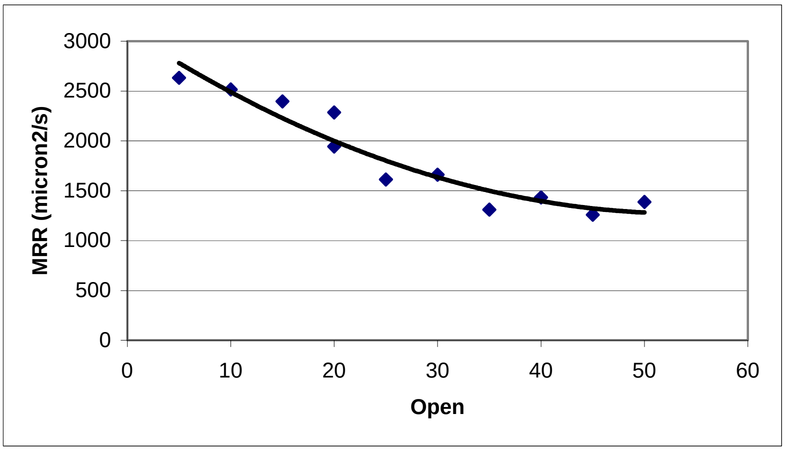


Figure E.4. Effect of Open on Material removal rate (MRR).

From figure E.4 the effect of open parameter on Material Removal Rate (MRR) is shown. As open parameter primarily affect the machining time, thus with increasing value of open, MRR decrease.

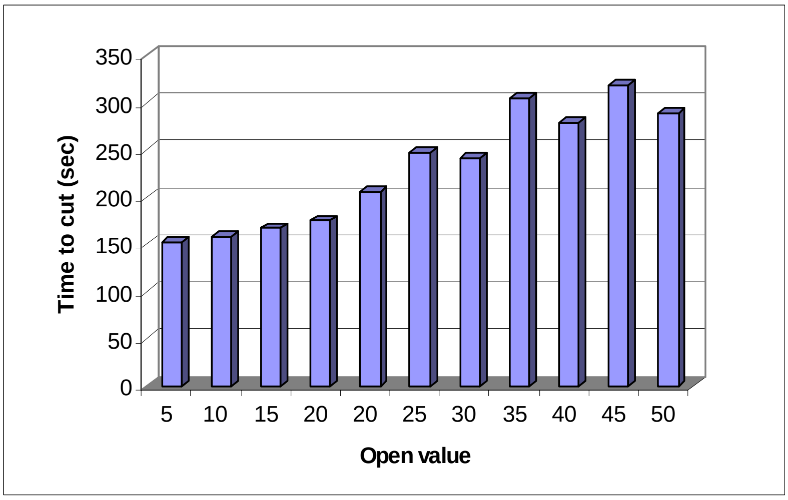


Figure E.5: Effect of Open on machining time

From figure E.5 it is clear that open value parameter has clear effect on machining time. As the value of Open is set high, it takes more time to erode the same amount of material given other parameters are kept same. Thus for faster machining result it is recommended that the open value should be set as low as possible. Since unlike other parameters in WEDM where faster machine means worse surface quality, open doesn't have such inverse relationship between machining time and surface quality.

E.9 Effect on Gap width

The value of gap width varies in very short range from 40 micron to 60 micron. This indicates that the effect of open parameter has little effect on the gap width, though it seems that with higher open value the gap width slightly increase. This may be because when retraction happens for more time with higher open value, after that when sparking resumes, additional spark occurs on the already eroded areas. This may lead to higher gap width when open parameter value increase.

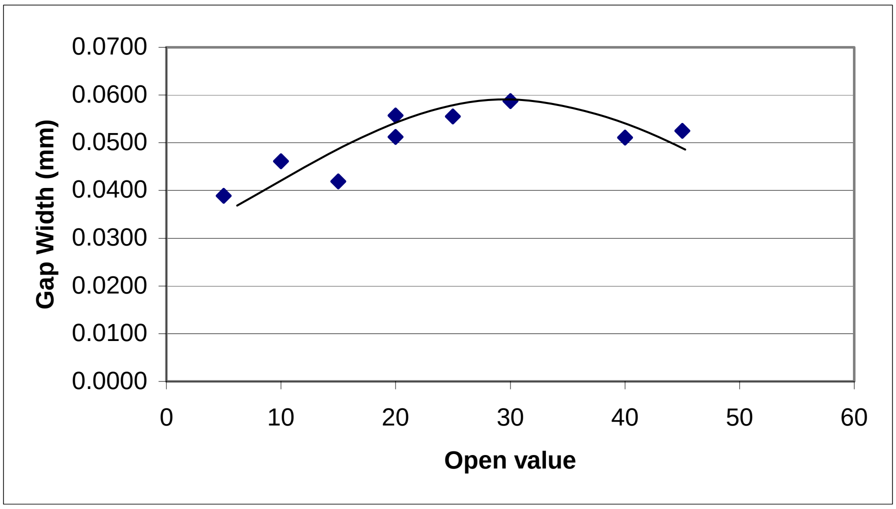


Figure E.6. Effect of open on gap width