EFFECT OF MACHINING PARAMETERS ON SURFACE TEXTURES IN WIRE ELECTRO DISCHARGE MACHINING OF AISI 4140 STEEL

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A report submitted in partial fulfilment of the requirements for the award of the degree of Bachelor of Mechanical Engineering

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JUDUL: **EFFECT OF MACHINING PARAMETERS ON SURFACE TEXTURES IN WIRE ELECTRO DISCHARGE MACHINING OF AISI 4140 STEEL**

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ABSTRACT

The Wire Electro Discharge Machining (WEDM) process is a violent thermal process where literally thousands of electrical discharges are produced in a fraction of a second in order to erode a certain volume of metal. The process is most used in situations where intricate complex shapes need to be machined in very hard materials (such as hardened tool steel). However, the process generates surface that have poor properties such as high tensile residual stresses, high surface roughness, presence of micro-cracks and micro-voids. These properties vary with different levels of the main machining parameters. The aim of this paper is to present experimental work that has been done in order to quantify the effect of some of the main WEDM parameters on the surface texture. 2D surface measurements were taken on all WEDM samples and 2D surface characterization has been carried out in order to calculate the different surface texture parameters. In this work, the surface characteristics caused by WEDM were analyzed by Scanning Electron Microscopy (SEM). An empirical model of AISI 4140 steel was proposed based on the experimental data. Surface roughness was determined with a 'Perthometer' recorder. Experimental results indicate that the WEDM process causes a ridged surface and induces machining damage in the surface layer and increases the surface roughness. The depth of micro-cracks and micro-voids increases with an increase in the amount of pulsed current and pulse-on duration. The effect of the magnitude of the pulse-on duration on the surface texture of the specimen is more significant than the pulsed current. Furthermore, the SEM reveals the two-dimensional image of surface textures of the WEDM specimen with a nanometer scale.

ABSTRAK

Proses Mesin Wayar Nyah-cas Elektrik (WEDM) adalah satu proses di mana berjuta-juta cas elektrik dihasilkan dalam masa yang sangat singkat untuk memotong/menghakis besi. Proses ini banyak diaplikasi dalam pembuatan bahan yang memerlukan bentuk yang kompleks dan juga bahan yg sangat keras. Walau bagaimanapun, proses ini menghasilkan sifat permukaan yang tidak sempurna seperti kekuatan tegangan yang tinggi, kekasaran permukaan yang tinggi, kehadiran retakan dan ruang kosong yang sangat halus. Kesemua sifat permukaan yang tidak sempurna ini akan berbeza apabila faktor pengehad yang digunakan dalam proses pemesinan berbeza. Tujuan kertas kerja ini adalah untuk mempersembahkan hasil eksperimen yang telah dijalankan bagi mengetahui kesan daripada faktor pengehad utama dalam WEDM kepada permukaan bahan. Pengiraan permukaan secara 2D telah diambil daripada semua sampel WEDM dan rupa bentuk permukaan secara 2D telah diambil untuk proses pengiraan faktor yang berbeza dalam sifat permukaan bahan. Dalam projek ini, sifat permukaan bahan yang telah dipotong dengan menggunakan WEDM dianalisis oleh SEM. Sebuah model daripada besi AISI 4140 telah disediakan berdasarkan data eksperimen. Kekasaran permukaan bahan ditentukan dengan menggunakan ‘Perthometer’. Hasil eksperimen menunjukkan proses WEDM menghasilkan permukaan yang berpuncak termasuk kerosakan semasa proses pemotongan dalam lapisan permukaan bahan dan ini akan mengakibatkan peningkatan nilai kekasaran permukaan. Kedalaman retakan dan ruang kosong di permukaan bahan akan meningkat apabila amaun arus dan masa mesin melakukan proses pemotongan meningkat. Faktor masa memberikan kesan yang lebih dominan kepada permukaan bahan berbanding dengan arus. SEM memperlihatkan imej permukaan bahan yang dipotong oleh WEDM secara dua dimensi dengan menggunakan skala nanometer.

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LIST OF SYMBOLS

$\boldsymbol{I_p}$	Pulsed current
$\boldsymbol{T_{on}}$	Pulse-on duration
R_a	Surface roughness
C_{max}	Depth of micro-cracks
V_{max}	Depth of micro-voids

LIST OF ABBREVIATIONS

WEDM	Wire Electro Discharge machining
SEM	Scanning Electron Microscopy
AISI	American Iron and Steel Institute
CNC	Computer Numerical Control
C	Carbon
Mn	Manganese
P	Phosphorus
S	Sulphur
Si	Silicon
Cr	Chromium
Mo	Molybdenum
CRT	Cathode Ray Tube
A	Ampere
V	Voltage
Pa	Pascal
AFM	Atomic Force Microscopy

CHAPTER 1

INTRODUCTION

1.1 Research background

Wire Electro Discharge Machining (WEDM) is one of the applications of EDM. This machine is generally uses a thin brass wire as the electrode, making it possible to cut most shapes and contour from flat plate material. WEDM can do things older technologies cannot do as well, as quickly as, as inexpensively, and as accurately. Most parts can now be programmed and produced as a solid, rather than in sections and then assembled as a unit, as was necessary previously. WEDM is capable of producing complex shapes such as tapers, involutes, parabolas and ellipses. WEDM utilizes a thin, continuously moving wire as an electrode as in Figure 1. The wire electrode is drawn from a supply reel and collected on a take-up reel. This continuously delivers fresh wire to the work area. The wire is guided by sapphire or diamond guides and kept straight by high tension, which is important to avoid tapering of the cut surface. High-frequency dc pulses are delivered to wire and workpiece, causing spark discharges in the narrow gap between the two. A stream of dielectric fluid is directed, usually coaxially with the wire, to flood the gap between the wire and the workpiece. The power supply for the WEDM are essentially the same as for conventional EDM, except the current carrying capacity of the wire limits currents to less than 20A, with 10A or less being most normal. In addition, the spark frequencies are higher, up to 1MHz, to give a fine surface on the workpiece [1,2].

AISI 4140 Steel also known as chromium molybdenum alloy steel is oil hardening steel of relatively high hardening ability and is among the most widely used versatile machinery steels. The AISI 4140 Steel is a structural material with a relatively high hardening ability, good hardness penetration and imparts uniformity of hardness and high strength. AISI 4140 Steel are one of the most capable material selections for versatile machinery steels as it is comparatively easy to machine in the heat treated condition. It is usually used to make shafts, gears, bolts, couplings, spindles, tool holders, hydraulic machinery shafts, oil industry drill collars, and tools joints [22].

The SEM is particularly useful in material analysis for the examination of fractured surfaces of metals. SEM fractograph are used to determine whether a fractured surface is intergranular, transgranular, or a mixture of both. The SEM is the most widely used from of electron microscope in the field of the materials sciences. More than 10,000 SEMs are installed worldwide and two new instruments are delivered each day. The SEM is popular because it uniquely combines some of the simplicity and ease of specimen preparation of the optical microscope with much of the performance capability and flexibility of the more expensive and complex transmission electron microscope.

1.2 Scope of study

This project concentrates on the surface texture of the material used that is AISI 4140 Steel after it has been cut using WEDM. The characteristics of the material such as the surface structure and surface texture can be seen from the Scanning Electron Microscope (SEM) directly. The surface textures vary with different levels of the main machining parameters.

1.3 Problem statement

WEDM process is a violent thermal process where literally thousands of electrical discharges are produced in a fraction of a second in order to erode a certain volume of metal. However, the process generates surfaces that have poor properties such as formation of a recast white layer, which is very hard and contains many imperfections such as cracks and micro cracks. These properties vary with different levels of the main machining parameters such as pulse current, pulse duration and the speed of the wire. The most appropriate machining parameters have to be determined to make sure that it will produce good surface textures.

1.4 Objectives

- To investigate the main machining parameter in WEDM such as pulse-on duration and pulsed duration.
- To quantify the effect of machining parameters on surface textures after being machined by WEDM.
- To determine the relationship between machining parameters and surface roughness, micro-cracks and micro-voids on the machined surface.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Chapter 2 is explains about the literature review of the project. This chapter includes about Wire Electro Discharge machining, Scanning Electron Microscopy to examined the surface textures, Taguchi Orthogonal Array, machining parameters, brass wire as the wire material, and AISI 4140 steel as the workpiece. A review of other relevant research studies is also provided. The review is organized chronologically to offer insight to how past research efforts have laid the groundwork for subsequent studies, including the present research effort. The review is detailed so that the present research effort can be properly tailored to add to the present body of literature as well as to justly the scope and direction of the present research effort.

2.2 Wire Electro Discharge Machining

Wire Electro-discharge Machining (WEDM) is an adaptation of the basic EDM process, which can be used for cutting complex two- and three-dimensional shapes through electrically conducting materials as we can see in Figure 2.1. WEDM utilizes a thin, continuously moving wire as an electrode referring to Figure 2.2. It is a relatively new process and applications have grown rapidly particularly in the tool making field. The wire electrode is drawn from a supply reel and collected on a take-up reel. This continuously delivers fresh wire to the work area. The wire is guided by sapphire or diamond guides and kept straight by high tension, which is important to avoid tapering of the cut surface [14].

Figure 2.1 : Wire Electro Discharge Machining [14]

High-frequency dc pulses are delivered to the wire and workpiece, causing spark discharges in the narrow gap between the two. A stream of dielectric fluid is directed, usually coaxially with the wire, to flood the gap between the wire and the workpiece. The power supplies for the WEDM are essentially the same as for conventional EDM, execp the current carrying capacity of the wire limits current to less than 20 A, with 10 A or less being most normal. In addition, the spark frequencies are higher up to 1 MHz, to give a fine surface finish on the workpiece [6].

The workpiece is moved under computer numerical control (CNC) referring to Figure 2.3 relative to the wire, and this enables complex-shaped profiles to be cut through sheet and plate materials. Many machines incorporate further angular positioning of the wire, thus, allowing varying degrees of taper on the cut surface to be obtained. Adaptive control, based on gap-voltage sensing, is necessary to avoid contact between the wire and the work material. Short circuits must be sensed and the wire backed off along the programmed path to reestablish the correct gap for efficient cutting [2,3].

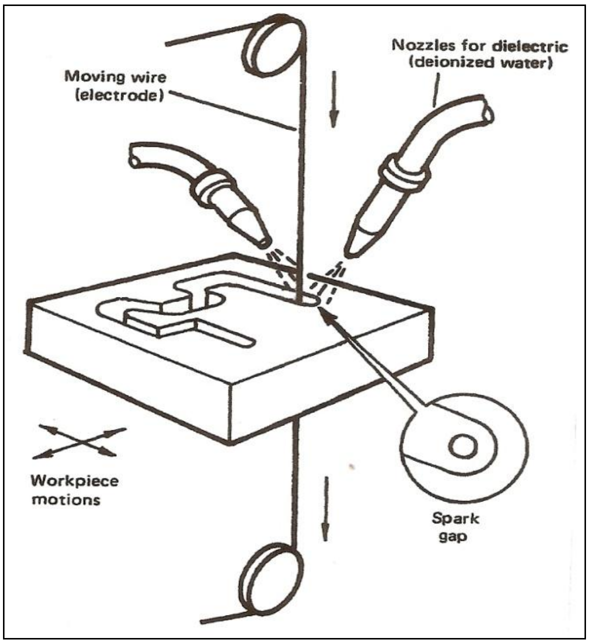

Figure 2.2 : The basic features of WEDM [14]

De-ionized water is the dielectric used for WEDM because it has low viscosity, presents no fire hazard, and results in high cooling rates and high material removal rates. A low viscosity is important to ensure adequate flow through the wire-workpiece gap to ensure efficiency to flushing. Copper and brass wire are commonly used for the electrodes, when the wire diameter is relatively large (0.15 - 0.30 mm). If very fine wire is required for high-precision cutting (0.03 – 0.15 mm), molybdenum- steel wire is used for increased strength. The wire-workpiece gap usually ranges from 0.025 to 0.05 mm and consequently the kerf width of cut made by WEDM is less than 0.1 mm plus the wire diameter [14].

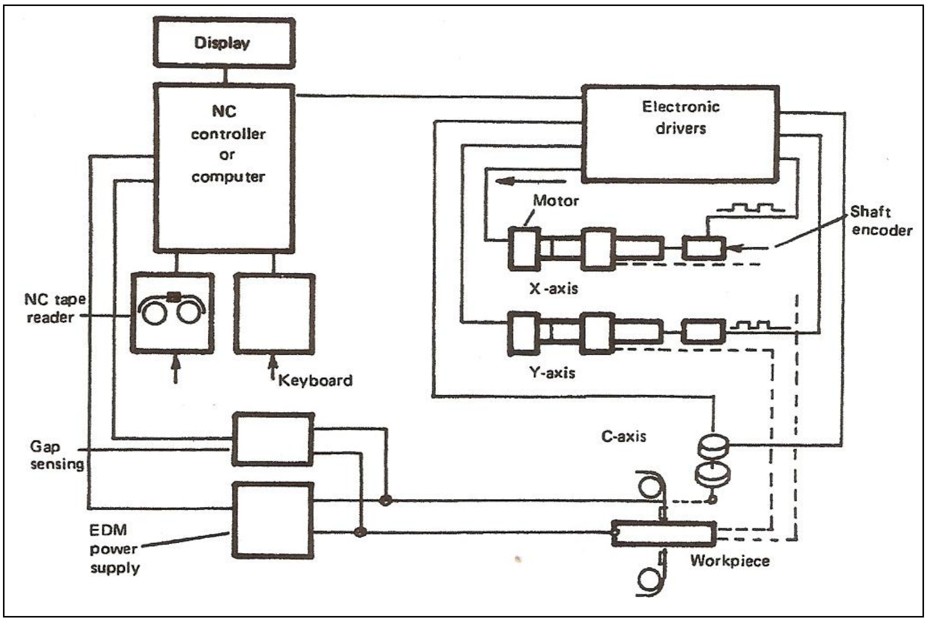

Figure 2.3 : Schematic of WEDM system [15]

WEDM is most commonly used for the fabrication of press stamping dies, extrusion dies, powder composition dies, profile gages, and templates. Complicated cutouts can be made in difficult-to-machine metals without the need for high-cost grinding or expensive shaped EDM electrodes. Linear cutting rates are relatively low, ranging, for example, from 38 to 115 mm/hr in 25 mm thick steel. However, the linear speed is dependent on the material being cut and not on the shape of the cut. Although WEDM is a relatively slow cutting process, this is compensated for by the complexity and the profiles that can be cut. Machines for WEDM are designed to operate unattended for long periods of time (often for several days) [15].

Accuracies in the cut-out profile of ±0.007 mm can be routinely obtained with WEDM, and this figure can be further reduced with special care, including ensuring uniformity of the wire diameter. The minimum internal corner radius possible is limited only by the wire diameter being used. External corners can be produced with radii as small as 0.038 mm [22].

2.3 Machining parameters

The machining parameter is the important part in WEDM that reveals the textures of the specimen after it has been cut. There are only two main of machining parameters that involves in this experiment which are pulsed current and pulse- on duration.

2.3.1 Pulse current

Metal removal rates, surface finish and accuracy are influenced mainly by the choice of electrical parameters. As the current is increased each individual spark removes a larger crater of workpiece material (Figure 2.4a), which increases the metal removal rate but also increases the surface roughness. Similar effects occur with increased spark voltage. Increasing the spark frequency, while keeping the other parameters constant, results in a decrease in surface roughness (Figure 2.4b), because the energy available is shared between more sparks, and smaller-sized surface craters are produced in the workpiece. The frequency range of modern WEDM machines is from 180 Hz, for roughing cuts, to several hundred kilohertz, for fine finishing. When the sparking frequency becomes very high, the dielectric fluid cannot de-ionize at a sufficiently high rate, placing an upper limit on the frequencies possible. Volumetric removal rates vary from 0.001 to 0.1cm^3/hr [15].

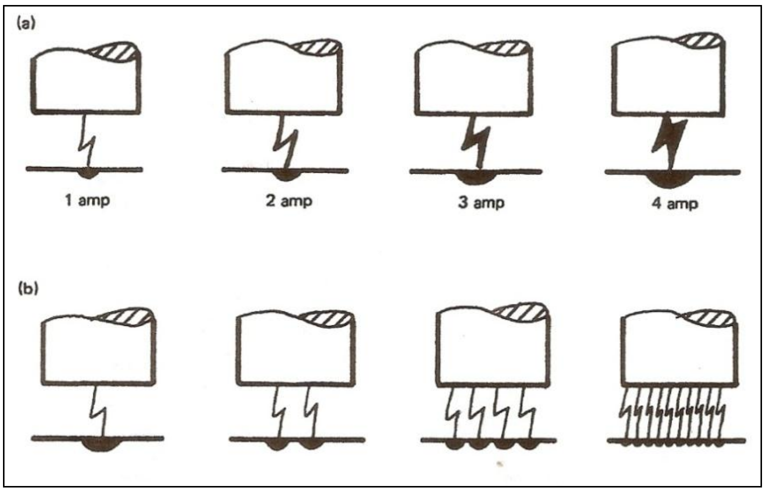

Figure 2.4 : Influence of current and pulsed frequency on surface finish

The accuracy of the process is closely related to the spark-gap width; the smaller the gap the higher the accuracy, but a smaller gap results in a lower working voltage and a lower removal rate. A compromise is thus necessary. Typical spark gaps range from 0.012 to 0.05 mm. As the gap decrease efficient flushing of the gap becomes more difficult to achieve.

The spark-machined surface, having a matte appearance similar to a shot-blasted surface, consists of very small spherical craters as a result of the metal being removed by individual sparks. The finish is therefore non-directional and very suitable for holding a lubricant [16]. Surface finishes of 0.25 μm and better have been obtained. A layer of melted and resolidified material, known as recast, is left on the surface produced by WEDM. This layer tends to be very hard and brittle. This recast layer is usually from 0.0025 to 0.05 mm in thickness and may have to be removed by other process if high levels of fatigue resistance are required [15].

2.3.2 Pulse-on duration and pulse-off duration

Figure 2.5 shows the ideal waveform of voltage between the workpiece and electrode versus time during EDM. As shown in Figure 2.5, the spark cycle, *T*, is the period of the spark, including both on time and off time. EDM uses a DC power supply and capacitor like energy storage bank to create the discharge. During the off time, *T*off, the capacitors are charged up and melted material is flushed from the gap between the wire electrode and workpiece. Then the circuit is completed, the spark is discharged, and the energy is delivered during the on time, *T*on, which is the spark on-time. This total time for charging and discharging is the spark cycle. This research studies the effect of *T*on and *T*on/*T* on EDM *MRR*. The gap voltage is the nominal voltage in the gap between the wire and workpiece [9,10].

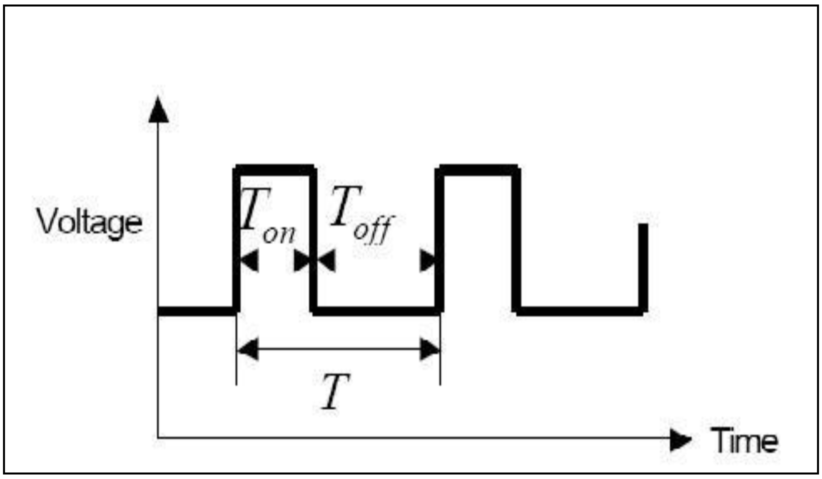

Figure 2.5 : Voltage vs duration during WEDM cutting process [22]

2.4 Material of the specimen and workpiece

This project needs to consider the material of the workpiece and the wire used in the WEDM as it is differ in the properties as gives different effect to the experiment.

2.4.1 Brass wire as the wire material

The brass wire is used in the experiment based on the mechanical properties which is very suitable to use as the wire material in WEDM. The range of the wire diameter is 0.1 to 0.33 mm and has two types which are hard brass wire and soft brass wire. In this project, the hard brass wire has been chosen due to its properties. It has tensile strength of 1030 N/mm^2 and elongation less than three percent. Furthermore, the breaking load is in between 3.14 to 3.30 kg which is quite high compare to the other types of material. Brass wire contains of a few chemical composition such as Copper (Cu), Zinc (Zn) and Ferum (Fe). Figure 2.6 below shows the example of brass wire that used in WEDM [17].

Figure 2.6 : Brass wire used in WEDM as the wire material [17]

2.4.2 AISI 4140 Steel as the workpiece

This AISI 4140 Steel also known as chromium molybdenum alloy steel is oil hardening steel of relatively high hardening ability and is among the most widely used versatile machinery steels. The chromium content provides good hardness penetration and the molybdenum imparts uniformity of hardness and high strength. This grade is especially suitable for forging as it has self scaling characteristics it responds readily to heat treatment and is comparatively easy to machine in the heat treated condition. In the heat treated condition tensile strengths are attended all combined with good ductility and resistance to shock. Table 2.1 shows the composition of AISI 4140 steel [15].

This steel maintains its properties even after long exposure at these relatively high working temperatures. The wear resistance can be considerably increased by flame hardening or induction hardening. A very interesting and powerful surface hardening process could be a combination of induction hardening with nitriding obtaining a real improvement of surface.

Table 2.1 : Composition of AISI 4140 steel [17]

Element	**Weight %**
C	0.38-0.43
Mn	0.75-1.00
P	0.035 (max)
S	0.04 (max)
Si	0.15-0.30
Cr	0.80-1.10
Mo	0.15-0.25

In the annealed condition AISI 4140 has a machinability rating of 66% of AISI B-1112. Average surface speed is 110 feet per minute. AISI 4140 steel is on the border line of weldability because of its relatively high carbon content. It can be welded by any of the common welding processes providing the section is preheated and stress relieved after welding. The grade of welding rod to be used depends upon the thickness of section, design and service requirements [17].

The mechanical properties of AISI 4140 steel such as density, Poisson's Ratio, Elastic Modulus, tensile strength are appropriate with the application in the engineering industry as hardened steel. The density of AISI 4140 steel is 7700 kg/m^3 while the Poisson's ratio is in between 0.27-0.30. It has elastic modulus of 190 GPa and tensile strength of 655 MPa. The hardness value is 197 HB and impact strength of 54.5 J after it has been annealed at 815 ˚C.

The thermal properties includes of thermal expansion, thermal conductivity and specific heat. The thermal expansion of AISI 4140 is 12.3 x 10^{-6} ˚C after it has been oil hardened and tempered at 600 ˚C. Thermal conductivity is 42.7 W/m.K and has specific heat of 473 J/kg.K [17].

2.5 Scanning Electron Microscope (SEM)

The scanning electron microscope (SEM) instrument that impinges a beam of electrons I a pinpointed spot on the surface of a target specimen and collects and displays the electronics signals given off by the target material. Figure 2.7 is a photograph of a recent model SEM. Basically, an electron gun produces an electron beam in an evacuated column that is focused and directed so that it impinges on a small spot on the target. Scanning coils allow the beam to scan a small area of the surface of the sample. Low-angle backscattered electrons interact with the protuberances of the surface and generate secondary backscattered electrons to produce an electronic signal, which in turn produces an image having a depth of field of up to about 300 times that of the optical microscope (about 10 m at 10,000 diameters magnification). The revolution of many SEM instruments is about 5 nm, with a wide range of magnification (about 15 to 100,000x) [11].

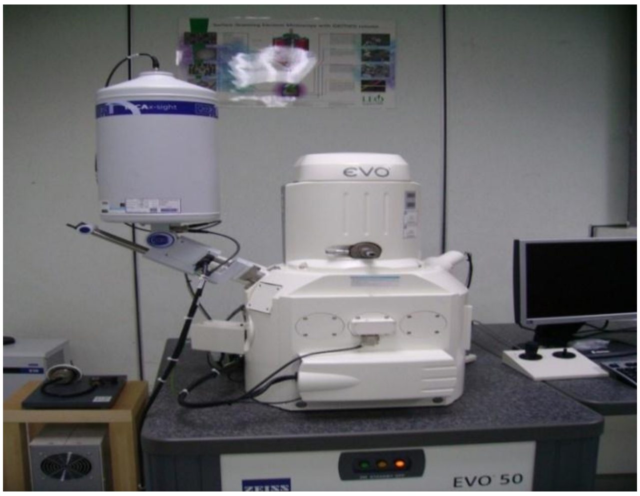

Figure 2.7 : Scanning Electron Microscope [11]

The SEM requires that specimens be conductive for the electron beam to scan the surface and that the electrons have a path to ground. All samples must also be trimmed to an appropriate size to fit in the specimen chamber and generally mounted on some sort of holder. Metals require little special preparation for SEM except for mounting on an appropriate specimen holder. Nonconductive solid specimens are coated with a layer of conductive material, except when observed with variable vacuum or Environmental SEMs. An ultra thin coating of electrically-conducting material such as, gold, gold/palladium alloy, platinum, tungsten or graphite is deposited on the sample either by low vacuum sputter coating or by high vacuum evaporation. This is done to prevent the accumulation of static electric charge on the specimen during electron irradiation. Another reason for coating, even when there is more than enough conductivity, is to improve contrast and resolution, a situation most common when using a FESEM (field emission SEM) and samples with low atomic number. Embedding in a resin with further polishing to a mirror-like finish can be used for both biological and materials specimens when imaging in backscattered electrons or when doing quantitative X-ray microanalysis. Figure 2.8 below shows SEM fractograph of AISI 4140 steel at 1000x magnification [22].

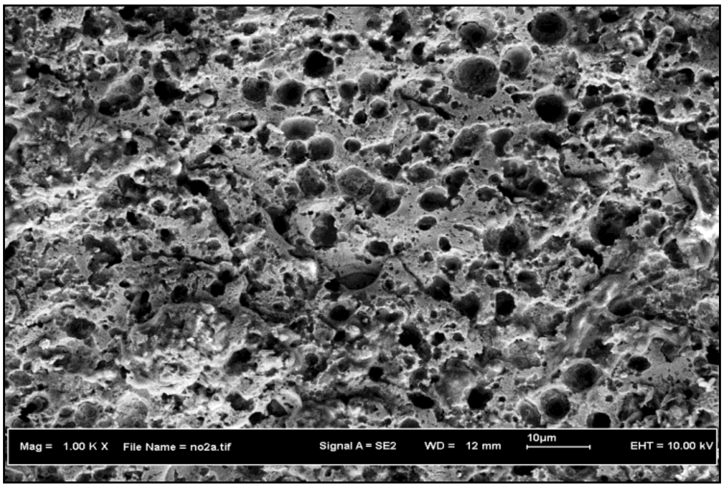

Figure 2.8 : SEM fractograph of AISI 4140 steel at 1000x magnification [22]

The SEM was originally devised in Germany in the 1930’s by Knoll and von Ardenne and can be considered as having had its origin in the early electrical facsimile machines then under development. Later, important developments were made by Zworykin, Hillier and Snyder at the RCA Research Laboratories in the USA in the 1940’s. The design and performance of their instrument anticipated much that was found in later microscopes, but their success was ultimately limited by the poor vacuum conditions under which they had to work. The current form of the instrument is the result of the work of Oatley and his students at Cambridge University between 1948 and 1965 [23].

2.6 Taguchi Orthogonal Array

The Taguchi method involves reducing the variation in a process through robust design of experiments. The overall objective of the method is to produce high quality product at low cost to the manufacturer. The Taguchi method was developed by Dr. Genichi Taguchi of Japan who maintained that variation. Therefore, poor quality in a process affects not only the manufacturer but also society. He developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied; it allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources. Analysis of variance on the collected data from the Taguchi design of experiments can be used to select new parameter values to optimize the performance characteristic [24].

The effect of many different parameters on the performance characteristic in a condensed set of experiments can be examined by using the orthogonal array experimental design proposed by Taguchi. Once the parameters affecting a process that can be controlled have been determined, the levels at which these parameters should be varied must be determined. Determining what levels of a variable to test requires an in-depth understanding of the process, including the minimum, maximum, and current value of the parameter. If the difference between the minimum and maximum value of a parameter is large, the values being tested can be further apart or more values can be tested. If the range of a parameter is small, then less value can be tested or the values tested can be closer together. Knowing the number of parameters and the number of levels, the proper orthogonal array can be selected. Using the array selector table shown below, the name of the appropriate array can be found by looking at the column and row corresponding to the number of parameters and number of levels. Once the name has been determined, the predefined array can be looked up [24].

Number of Levels	Number of Parameters (P)																													
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
2	L4	L4	L8	L8	L8	L8	L12	L12	L12	L12	L16	L16	L16	L16	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32	L32
3	L9	L9	L9	L18	L18	L18	L18	L27	L27	L27	L27	L27	L36	L36	L36	L36	L36	L36	L36	L36	L36	L36								
4	L'16	L'16	L'16	L'16	L'32	L'32	L'32	L'32	L'32																					
5	L25	L25	L25	L25	L25	L50	L50	L50	L50	L50	L50																			

Figure 2.9 : Number of parameters and levels on the Taguchi Orthogonal Array [24]

An advantage of the Taguchi method is that it emphasizes a mean performance characteristics value close to the target value rather than a value within certain specification limits, thus improving the product quality. Additionally, Taguchi's method for experimental design is straightforward and easy to apply to many engineering situations, making it a powerful yet simple tool. It can be used to quickly narrow down the scope of a research project or to identify problems in a manufacturing process from data already in existence. Also, the Taguchi method allows for the analysis of many different parameters without a prohibitively high amount of experimentation. In this way, it allows for the identification of key parameters that have the most effect on the performance characteristic value so that further experimentation on these parameters can be performed and the parameters that have little effect can be ignored [24].

The main disadvantage of the Taguchi method is that the results obtained are only relative and do not exactly indicate what parameter has the highest effect on the performance characteristic value. The Taguchi method has been criticized in the literature for difficulty in accounting for interactions between parameters [24].

CHAPTER 3

METHODOLOGY

3.1 Introduction

Chapter 3 explains about the methodology from the beginning of the project until the end. After the title of this project has been discuss with the supervisor, all the processes is identified step by step before it can be proceed with the experiment. The first step was the face of the workpiece must be milled using milling machine due to smooth the surface of the specimen. Besides that, the dimension of the workpiece can be set accurately to make it easy to clamp on the WEDM. The second step, Taguchi Orthogonal Array has been used for the design of the experiment. Three levels of each factor were chosen for the 9 experiments. After that, workpiece is cut using WEDM for 9 times with different machining parameters. The machining parameters used are pulse-on duration and pulsed current. The other parameters such as flushing pressure, wire speed, pulse-off duration was maintained constant during the experiments. After all 9 cutting has done, the specimens must been examined by SEM to see the surface textures. The next step was collected the data and analyzed the result by doing the graph. The data collected were the surface roughness, micro-cracks and micro-voids. Finally, the conclusion must be done to conclude the result and discussion. The methodology of this project has been summarized in the Figure 3.1 below.

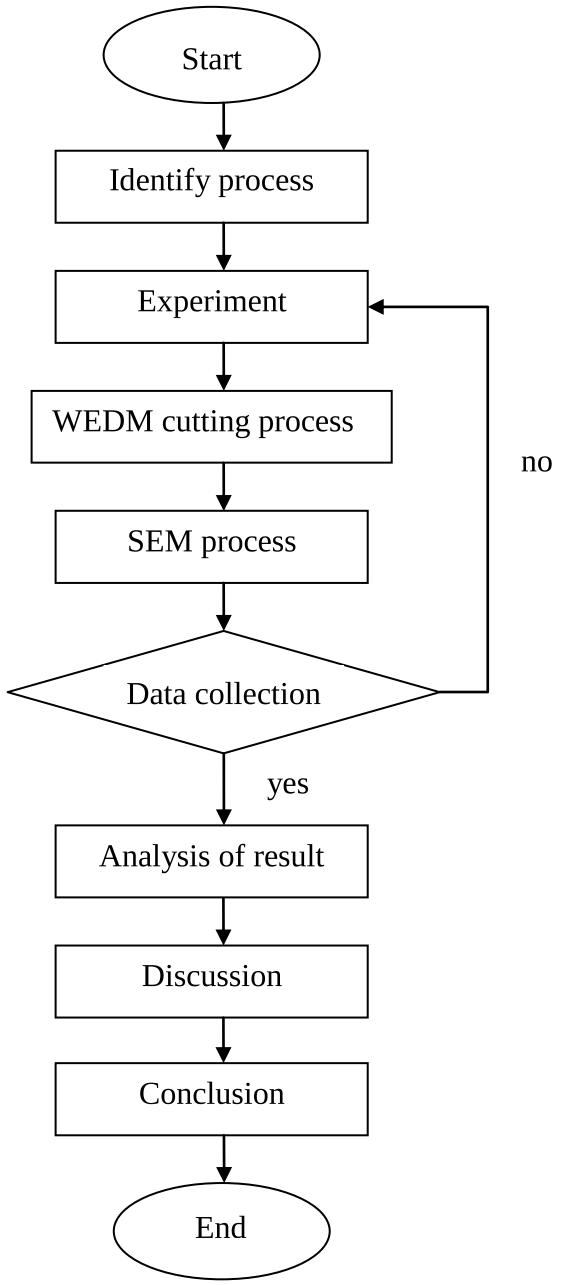

Figure 3.1 : Flow chart outlining the step taken in this project

3.2 Flow chart for the experiments

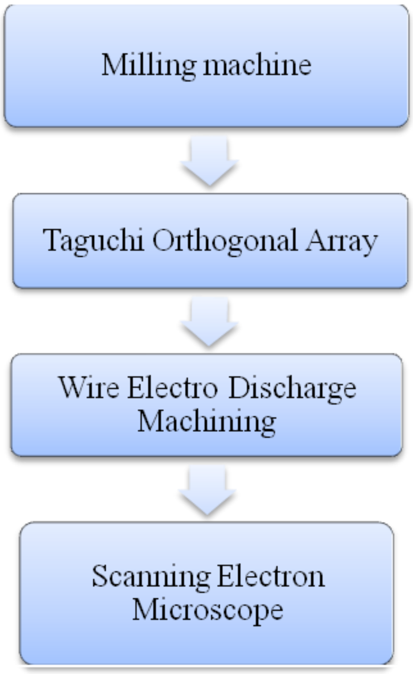

Figure 3.2 : Flow chart for the whole experiments

Figure 3.2 explains about the steps of experiment that has been done in this project. Milling machine is used to smooth the surface of the specimen before it can be proceed to the WEDM cutting process. Taguchi Orthogonal Array is used to design the experiment that should be run during WEDM process. There are nine experiments to be done. After that, the workpiece is cut using WEDM with different machining parameters. As soon as the workpiece has been cut, the specimen is examined using SEM to see the surface textures.

3.3 Milling machine

The milling machine was used to smooth the surface of the workpiece before it can be proceed with the experiment. Furthermore, the dimension of the workpiece can be set accurately to make it easy to clamp on the WEDM. Besides that, it can avoid error in the readings when the experiments have been done. Milling is the process of cutting away material by feeding a workpiece past a rotating multiple tooth cutter. The cutting action of the many teeth around the milling cutter provides a fast method of machining. In face milling, the cutter is mounted on a spindle having an axis of rotation perpendicular to the workpiece surface. The milled surface results from the action of cutting edges located on the periphery and face of the cutter. The example of face mill process can be seen in Figure 3.3 below [12].

Figure 3.3 : Face milling process [12]

3.4 Taguchi Orthogonal Array

The Taguchi's Robust Design was used for the design of the experiment. Three levels of each factor were chosen, L9 orthogonal array was designed for the experiment. Table 3.1 show three levels of each variable were used in the experiment while table 3.2 shows the machining condition (pulsed current and pulse-on duration) for the 9 experiments designed by L9 Taguchi Orthogonal Array [21]

Table 3.1 : Levels of independent variables in WEDM experiment

Level	**Pulsed current (A)**	**Pulse-on duration (μs)**
1	1.5	3.2
2	5.0	6.4
3	12.5	12.0

Table 3.2 : L9 Orthogonal Array for the WEDM experiment

Experiment no.	**Pulse-on duration, I_p (A)**	**Pulsed current, T_{on} (μs)**
1	1.5	3.2
2	1.5	6.4
3	1.5	12.0
4	5.0	3.2
5	5.0	6.4
6	5.0	12.0
7	12.5	3.2
8	12.5	6.4

9	12.5	12.0

3.5 Wire Electro Discharge Machining cutting process

The WEDM experiments were performed on a WEDM machine model type .A number of process variables can be investigated during the WEDM process. Following some of the findings of preliminary experiments and also based on literature survey, only two independent variables, namely, pulsed current and pulse-on duration, were varied, both of which were settings of the power supply.

The experiments were conducted in de-ionized water by immersing the workpiece to a depth of 35 mm. A thin brass wire of 0.20 mm in diameter was used as tool for cutting the workpiece. The brass wire served as the negative polarity and the specimen served as the positive polarity during the WEDM process. The specimen was cut from a rectangular bar of AISI 4140 steel with dimension 200 x 40 x 15 mm using WEDM cutting process. Table 3.3 shows the wire electo-discharge machining conditions. The machining voltage was maintained at 80 V, off-time duration at 100 μs and flushing pressure at 0.1 MPa. The other two parameters were maintained at three levels; current setting at 1.5, 5.0 and 12.5 A; and on-time duration at 3.2, 6.4 and 12.0 μs.

Table 3.3 : Experimental conditions for WEDM

Dielectric	de-ionized water
Work material	AISI 4140 Steel
Wire material	brass (0.20 mm)
Pulse-off duration	10 µs
Voltage	80 V
Wire speed	15 mm/min
Flushing pressure	0.1 MPa
Pulsed current	1.5, 5.0, 12.5 A
Pulse-on duration	3.2, 6.4, 12.0 µs

For every trial of the nine experiments, a specimen was prepared by cutting 10 mm length of workpiece using the WEDM process. During the WEDM process, the pulse-off duration setting 10 µs could effectively control the flushing of the debris from the gap, offering machining stability. Hence, the effect of the pulse-off duration on the machined characteristics was not considered in the present work.

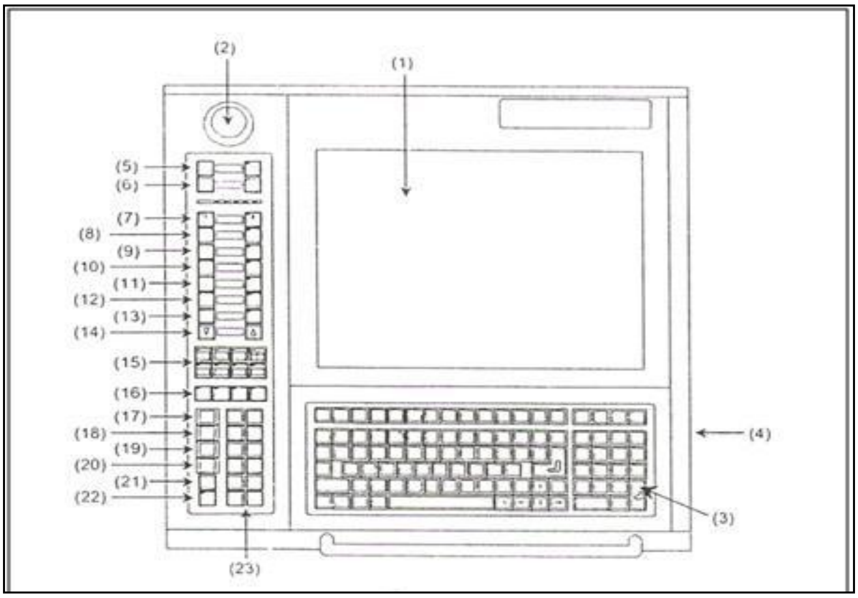

Figure 3.4 : Operation panel of WEDM [9]

(1)	LCD screen	(13)	[TANK DRAIN]
(2)	Emergency stop switch	(14)	[TANK DOOR]
(3)	Keyboard	(15)	Switches [A0] to [A7]
(4)	Floppy disc drive	(16)	Switch [MFR0]
(5)	[SOURCE ON/OFF] switches	(17)	[OFF] switch
(6)	[POWER ON/OFF] switches	(18)	[ACK] switch
(7)	[AWT CUT/TREAD] switch	(19)	[HALT] switch
(8)	[TENSION ON/OFF] switches	(20)	[ENT] switch
(9)	[WIRE STOP/RUN] switches	(21)	[ST] switch
(10)	[HIGH PRESSURE ON/OFF] switches	(22)	[UV] switch
(11)	[LOW PRESSURE ON/OFF] switches	(23)	Jog switches
(12)	[TANK FILL ON/OFF]		

Figure 3.4 shows the operation panel of WEDM that should be known by users. The LCD screen displays various information relating to the machine and the power supply, guidance on machine operation. The emergency stop switch must be pressed immediately to stop the machine when personnel appear to be in danger or when there seems to be something wrong with the machine. All personnel must understand the function of the emergency stop switch and be prepared to press it

immediately in the event of an emergency. To protect the machine, at least two minutes of time have to be allowed between pressings of the source on and source off and vice versa. The federate corresponding to each switch can be set in the Setting mode. The status corresponding to the switch whose lamp is on is the effective status [9].

3.6 Scanning Electron Microscopy

Sample 40 x 40 mm^2 strip is generally mounted rigidly on the specimen holder called a specimen stub. The sample is placed in a small chamber which is at vacuum column through an air-tight door. Before that, all water, solvents or other materials that could vaporize while in the vacuum must be removed. When a SEM is used, the column must always be at vacuum. There are many reasons for this. If the sample in a gas filled environment, an electron beam cannot be generated or maintained because of a high instability in the beam. The final image is built up from the number of electrons emitted from each spot on the sample [11].

CHAPTER 4

RESULT AND DISCUSSION

4.1 Surface morphology

Surface morphology plays an important part in understanding the characteristics of machined surfaces. During WEDM process, the discharged energy produces very high temperatures at the point of the spark, causing a minute part of the specimen to melt and vaporize. With each discharge, a crater is formed on the machined surface. The surface morphology is a function of two parameters, pulsed current and pulse-on duration, both of which are settings of the power supply.

SEM was conducted in order to evaluate the effect of machining parameters on the surface textures of the AISI 4140 steel. Figure shows the two-dimensional SEM image of the machined surface obtained from the WEDM specimens. The darker contrast corresponds to the lower areas of surface, and the brighter corresponds to the higher. It is clear that the morphology of the WEDM surface was dependent on the applied pulsed current and pulse-on duration. Moreover, The WEDM surfaces abound with the craters and ridged surfaces.

The craters and ridge-rich surfaces were formed by melted material, which was blasted out of the surface by the discharge pressure and subsequently quickly reached solidification temperature through being cooled by the surrounding working fluid. When a smaller pulsed current and pulse-on duration were applied, the surface characteristics had minor hillocks and valleys. When the pulsed current and pulse-on duration increased, the machined surface exhibited deeper craters and ridge-rich surfaces.

Previous work has observed a similar phenomenon [11]. This phenomenon might be attributable to a higher pulsed current and a longer pulse-on duration causing more frequent cracking of the dielectric fluid, as there was more frequent melt expulsion leading to the formation of deeper and larger craters on the surface of the workpiece. Figure 4.1 and Figure 4.2 shows the SEM image with different levels of machining parameters of the maximum and minimum value of surface roughness, depth of micro-cracks and micro-voids.

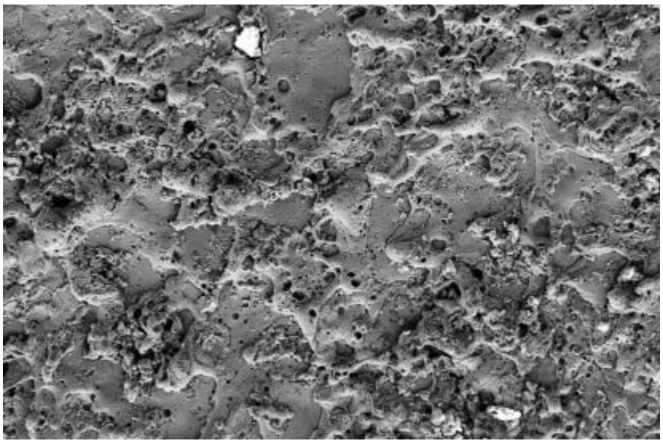

Figure 4.1: SEM image of the minimum value of surface roughness

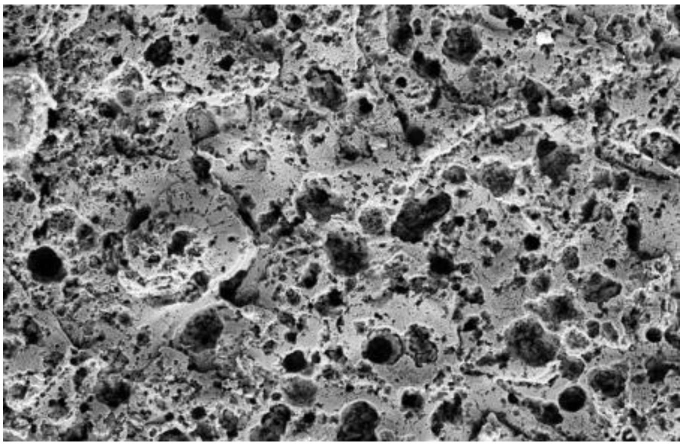

Figure 4.2: SEM image of the maximum value of surface roughness

4.2 Surface roughness

Surface roughness is a critical parameter for evaluating machined quality. To determine the effect of the WEDM process on the surface roughness of the AISI 4140 steel, the surface profiles of the WEDM specimens were measured by perthometer and SEM. The value of the surface roughness, *Ra*, of the machined specimen was calculated according to Eq. (1)

$$R_a = 21.00(I_p)^{0.33}(\tau_{on})^{1.37} \tag{1}$$

where R_a is the surface roughness, I_p denotes the pulsed current and τ_{on} represents the pulse-on duration. The surface roughness on the machined surface varied from 118.14 to 1454.38 nm (Table 4.1). From these results it is obvious that a higher pulsed current and longer pulse-on duration caused a poorer surface finish.

Figure 4.3 shows that graph surface roughness at various machining conditions. It was found that an excellent machined finish can be obtained by setting the machine parameters at low pulsed current and small pulse-on duration. This can be attributed to the fact that as the pulsed current decreases, discharges strike the surface of the sample less intensely, and the resulting better erosion effect leads to smoother surface. Furthermore, as the pulse-on duration decreases, the amount of heat energy transferred to the sample surface decreases, and so less material melts. The fact that the surface roughness decreases with decreasing discharge energy has been described in the literature [10,11,12].

Table 4.1 : Result of surface roughness for nine specimens

Experiment no.	Pulse-on duration, I_p (A)	Pulsed current, T_{on} (μs)	Surface roughness, R_a (nm)
1	1.5	3.2	118.14
2	1.5	6.4	305.35
3	1.5	12.0	722.45
4	5.0	3.2	175.77
5	5.0	6.4	368.54
6	5.0	12.0	1074.87
7	12.5	3.2	237.82
8	12.5	6.4	614.70
9	12.5	12.0	1454.38

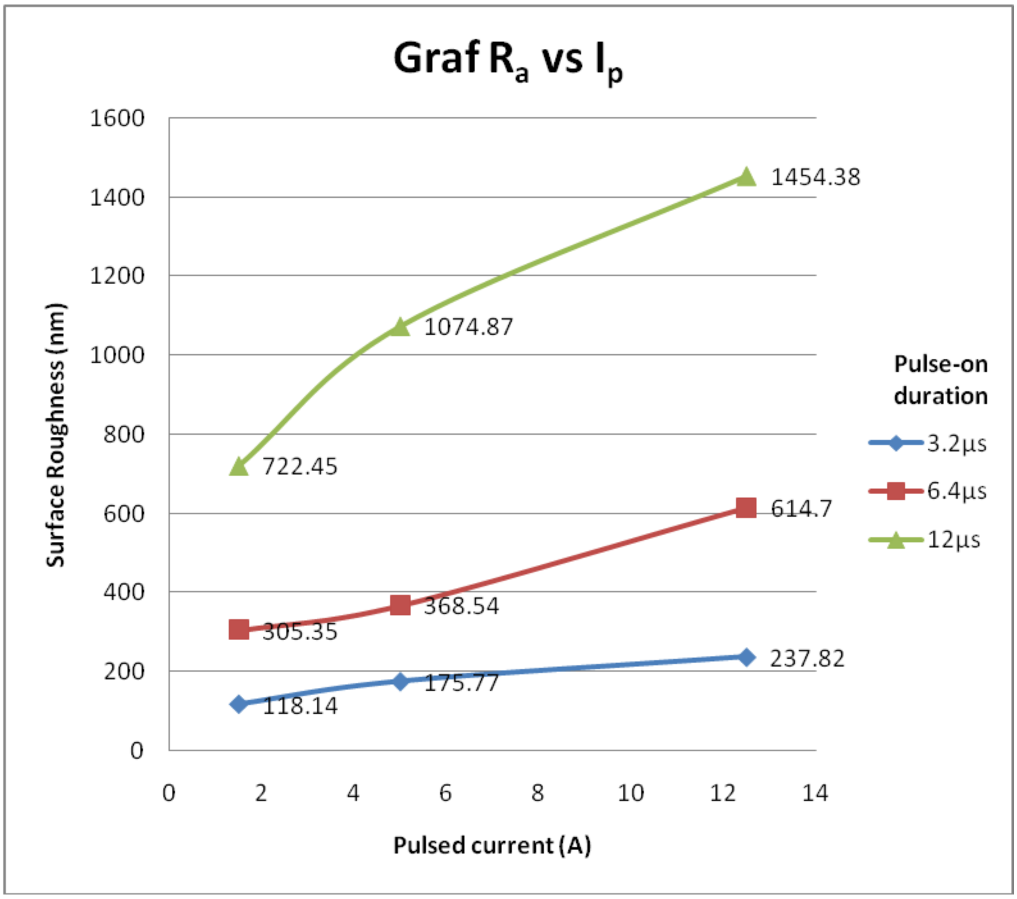

Figure 4.3 : Graph surface roughness at various machining condition

4.3 Micro-cracks

The WEDM-cut surface is covered with cracks and micro-cracks. The depth of the cracks terminates within the white layer. Cracks and micro-cracks in the WEDM specimens are undesirable as they reduce the service strength of the machined component. The micro-cracks were associated with the development of thermal stresses exceeding the ultimate tensile strength of the material. The primary causes of the thermal stress in the machined surface were the drastic heating and cooling rates and the non-uniform temperature distribution. Figure 4.4 shows the dependence of the maximum depth of micro-cracks on the WEDM parameters. The figure shows that the depth of the micro-cracks on the WEDM specimen ranged from 648.33 to 1594.45 nm, increasing with the pulsed current and pulse-on duration. The correlation between the maximum depth of the micro-cracks, C_{max}, and the machining conditions was calculated according to Eq (2) :

$$C_{max} = 393.30\, (I_p)^{0.20}\, (\tau_{on})^{0.36} \qquad (2)$$

Table 4.2 : Result of depth of micro-cracks for nine specimens

Experiment no.	**Pulse-on duration, I_p (A)**	**Pulsed current, T_{on} (µs)**	**Depth of micro-cracks, C_{max} (nm)**
1	1.5	3.2	648.33
2	1.5	6.4	832.08
3	1.5	12.0	1043.39
4	5.0	3.2	824.84
5	5.0	6.4	1058.63
6	5.0	12.0	1327.47
7	12.5	3.2	990.74
8	12.5	6.4	1271.54
9	12.5	12.0	1594.45

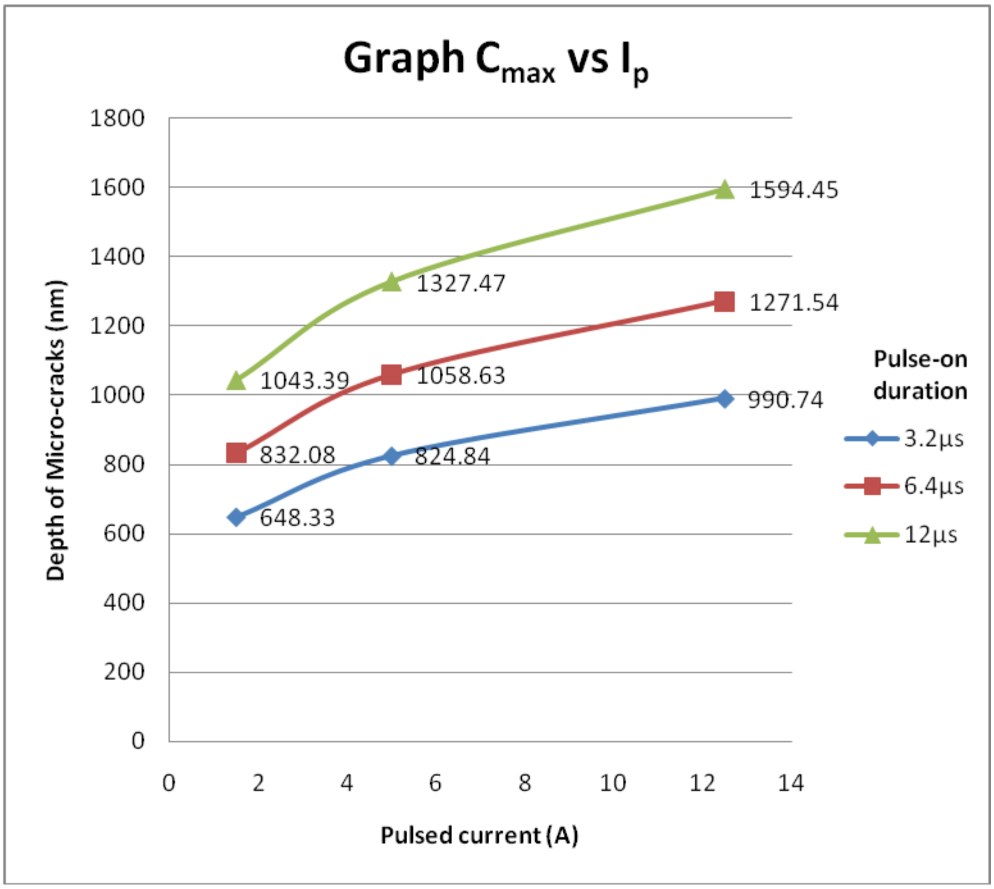

Figure 4.4 : Graph depth of micro-cracks at various machining conditions

4.3 Micro-voids

The maximum depth of micro-voids of 840.52 to 13493.4 nm was found on the WEDM surface (Table 4.3). The depth of voids clearly increased with the increase in energy supply. This is because of the fact that heat supplied to the workpiece due to sparks is higher at larger pulsed current and pulse-on duration, and hence increased the voids degree. Using eq. (3) to determine the correlation between the maximum depth of the micro-voids, Vmax, and the machining parameters :

$$V_{max} = 158.41\,(I_p)^{0.53}\,(\tau_{on})^{1.25} \tag{3}$$

This semi-empirical model indicates that the pulse-on duration has more dominant effect on the maximum depth of the micro-voids compared to the pulsed current. Comparing the results of Figure 4.4 and Figure 4.5, it was found that the depth of the micro-voids was greater than the depth of the micro-cracks.

Table 4.3 : Result of depth of micro-voids for nine specimens

Experiment no.	**Pulse-on duration, I_p (A)**	**Pulsed current, T_{on} (μs)**	**Depth of micro-cracks, V_{max} (nm)**
1	1.5	3.2	840.52
2	1.5	6.4	1999.11
3	1.5	12.0	4386.19
4	5.0	3.2	1591.01
5	5.0	6.4	3784.09
6	5.0	12.0	8302.58
7	12.5	3.2	2585.73
8	12.5	6.4	6149.93
9	12.5	12.0	13493.40

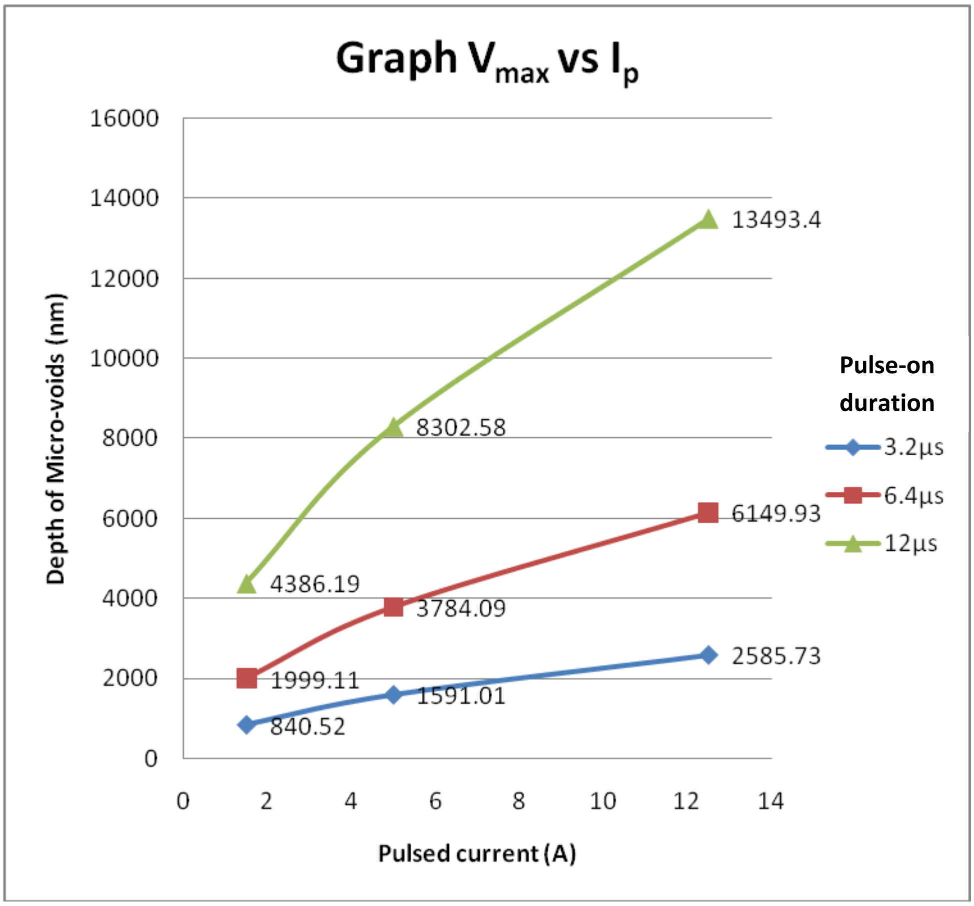

Figure 4.5 : Graph depth of micro-voids at various machining conditions

CHAPTER 5

CONCLUSION

5.1 Conclusion

In this project, the relative importance of two main machining parameter variables in WEDM has been identified. Based on the obtained findings, the SEM can be successfully applied to obtain a two-dimensional image with a nanometer scale. The surface roughness of the machined surface can be determined by examine the specimen using pethometer recorder. AISI 4140 steel was cut into nine specimens with different machining parameters which are pulsed current and pulse-on duration.

From the data collected and analysed, it can be concluded that the pulse-on duration has major influence in defining the WEDM surface texture as compared to the pulsed current. Moreover, the interaction effect between pulsed current and pulse-on duration on the 2D surface roughness parameters is relatively small. Through analysis on SEM and calculation, it has been observed that the value of surface roughness, depth of micro-cracks and micro-voids slightly increased with time taken.

The higher discharge energy caused more frequent melting expulsion, leading to the formation of a deeper and larger crater on the surface of the workpiece, and resulted in a poorer surface finish. Based on the obtained formula, the values of surface roughness, depth of micro-cracks and micro-voids produced by the WEDM could be evaluated. Moreover, the effect of the magnitude of the pulse-on duration on the surface texture of the specimen was more dominant than the pulsed current.

Thus another experiment needs to be done with pulsed current and pulse-on duration expanding from small values (about 0.2 A and 1.2 μs, respectively) to the maximum values. This should give us better idea about the trend of the surface texture variation at lower pulse energies. Moreover, better understanding of the mathematical correlation between surface roughness and the main machining parameters can be obtained as well as the physical phenomenon, which takes place during the discharge under different machining conditions.

Overall, there are a few steps that can be done more details to produce a good surface finish such as the WEDM machining parameters should be set at low pulsed-current and small pulse-on duration. Once the specimens have been cut, it must be examined instantly to avoid corrosion at the surface which is leads to the bad surface finish. Besides that, the perthometer recorder should be use gently so that the readings can be obtained accurately due to its high sensitivity.

5.2 Recommendation

After the experiment was finished completely, there are a few steps that should be done to improve the experiment :

- The Atomic Force Microscopy (AFM) technique can be applied to obtain three-dimensional image so that the surface textures can be examined in more details.
- ANOVA technique can be used to assess the quantitative influence of the different machining parameters on WEDM.
- Electrochemical polishing (ECP) is one technique that is used mainly to improve the appearance of steels as well as for passivation of stainless steels besides using WEDM process.

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APPENDICES

Figure 6.1 : WEDM machine

Figure 6.2 : Specimen before the WEDM cutting

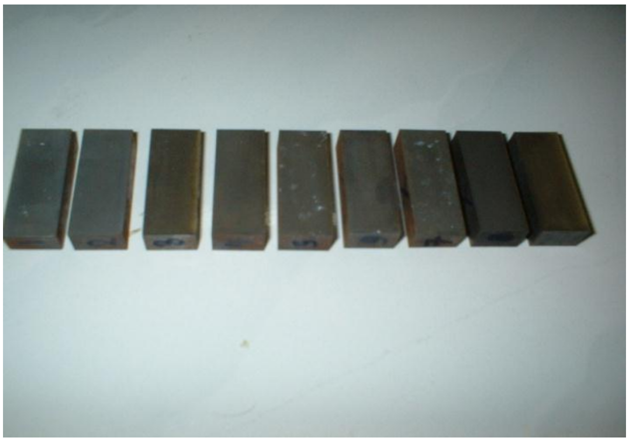

Figure 6.3 : Specimen after the WEDM cutting

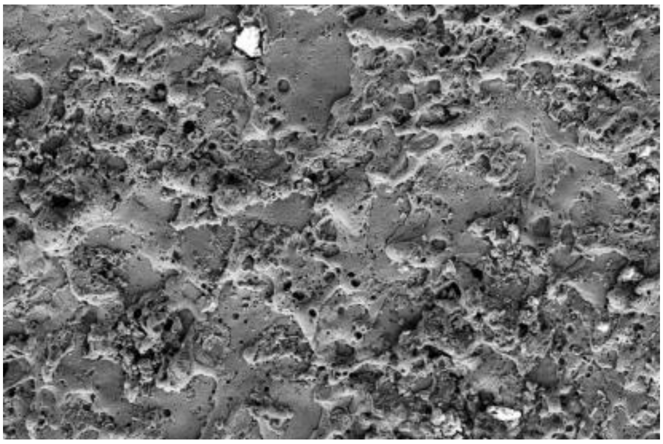

Figure 6.4 : SEM image with 1000x magnification at 1.5 A and 3.2 μs

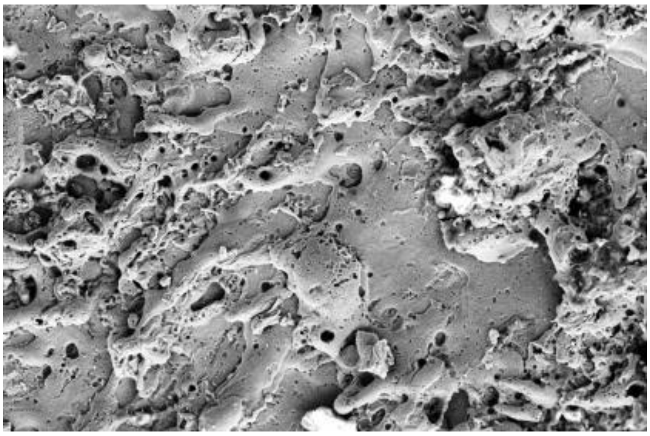

Figure 6.5 : SEM image with 1000x magnification 1.5 A and 6.4 μs

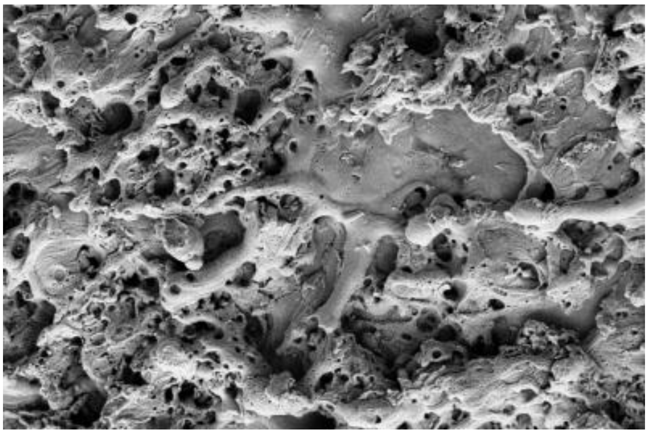

Figure 6.6 : SEM image with 1000x magnification 1.5 A and 12.0 μs

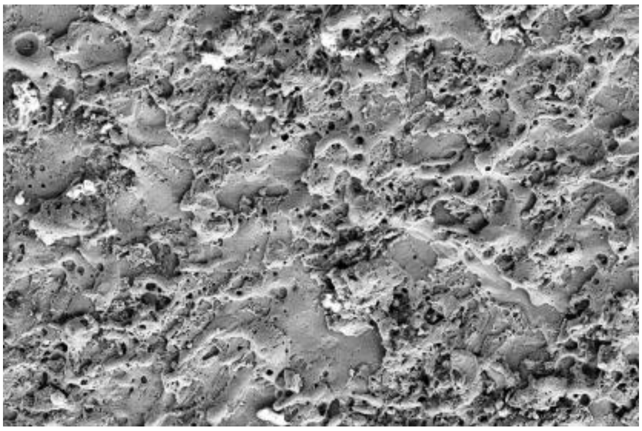

Figure 6.7 : SEM image with 1000x magnification 5.0 a and 3.2 µs

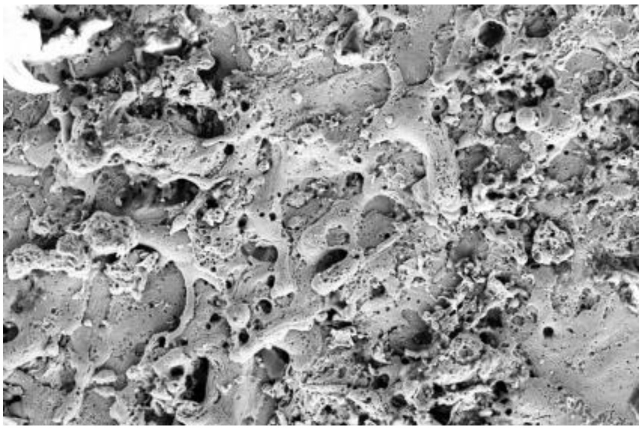

Figure 6.8 : SEM image with 1000x magnification 5.0 A and 6.4 µs

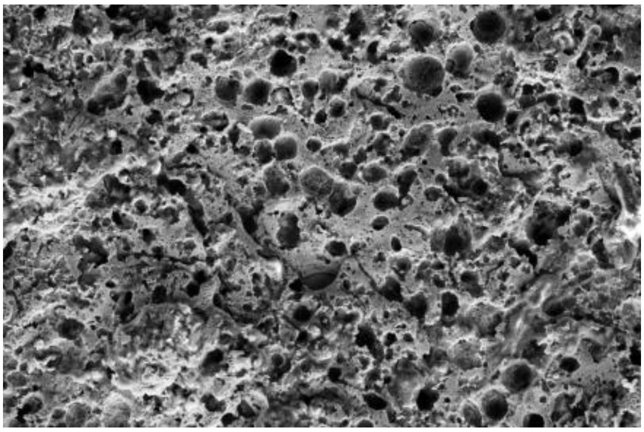

Figure 6.9 : SEM image with 1000x magnification 5.0 A and 12.0 µs

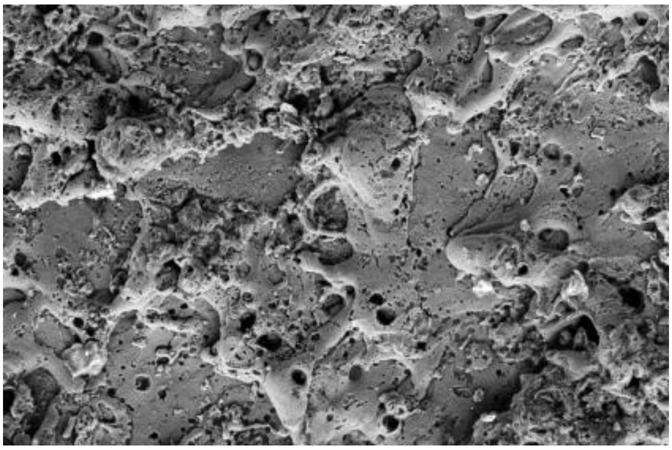

Figure 6.10 : SEM image with 1000x magnification 12.5 A and 3.2 μs

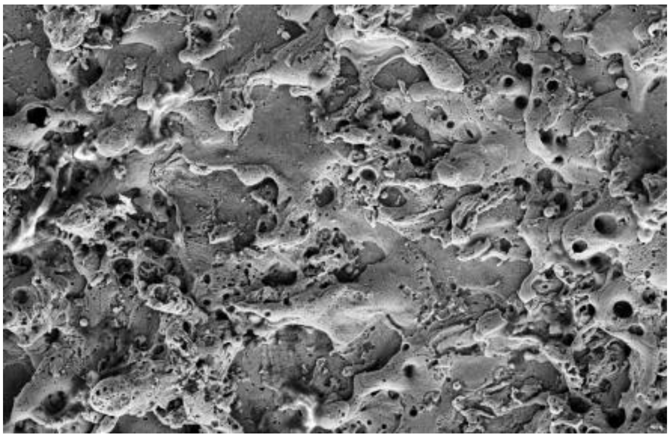

Figure 6.11 : SEM image with 1000x magnification 12.5 A and 6.4 μs

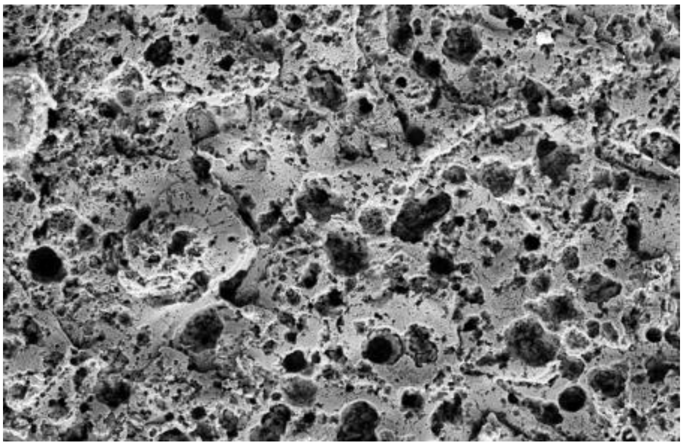

Figure 6.12 : SEM image with 1000x magnification 12.5A and 12.0 μs