ANALYSIS OF THE INFLUENCE OF EDM PARAMETERS ON SURFACE QUALITY,MRR AND EW OF WC–CO

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A project report submitted in partial fulfillment
of the requirements for the award of the degree of
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SUPERVISOR'S DECLARATION

We hereby declare that we have checked this project and in our opinion this project is satisfactory in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering with Manufacturing.

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STUDENT'S DECLARATION

I hereby declare that this project report entitled "Analysis of the influence of edm parameters on surface quality, MRR and EW of WC–Co" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted for award of other degree.

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Special dedicated to my late mother, Allahyarhamah Zalehar binti Boto', my beloved father, Khalid bin Awang and family,my friends

&

my supervisor, Puan Mas Ayu binti Hassan

for their support and care.

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ABSTRACT

Electrical discharge machining (EDM) is a process for shaping hard metals and forming deep complex shaped holes by arc erosion in all kinds of electro-conductive materials. The objective of this research is to study the influence of operating parameters of EDM of tungsten carbide on the machining characteristics such as surface quality,material removal rate and electrode wear. The effectiveness of EDM process with tungsten carbide,WC-Co is evaluated in terms of the material removal rate,the relative wear ratio and the surface finish quality of the workpiece produced. It is observed that copper tungsten is most suitable for use as the tool electrode in EDM of WC-Co. Better machining performance is obtained generally with the electrode as the cathode and the workpiece as an anode. In this research, a study was carried out on the influence of the parameters such peak currrent,power supply voltage,pulse on time and pulse off time. The surface quality that was investigated in this experiment was surface roughness using perthometer machine. Material removal rate (MRR) and electrode wear (EW) in this experiment was calculated by using mathematical method. The result of the experiment then was collected and analyzed using STATISTICA software. This was done by using the technique of design of experiments (DOE) and technique such as ANOVA analysis. This analysis was purposed to select the optimal machining condition for use in confirmation test. The confirmation test was purposed to evaluated the error margin between predicted result by software and confirmation result by experiment in terms of the machining characteristics.

ABSTRAK

Proses pemesinan nyahcas elektrik adalah proses untuk membentuk logam keras dan membuat bentuk lubang dalam yang kompleks oleh cas elektrik untuk semua jenis logam yang elektro-konduktif. Objektif kajian ini adalah untuk mengkaji pengaruh parameter yang digunakan oleh EDM terhadap tungsten karbida dari segi kualiti permukaan, kadar pembuangan material (MRR) dan nisbah kehausan elektrod (EW). Keberkesanan proses EDM dengan tungsten karbida,WC-Co di nilai dari segi MRR, EW dan kualiti permukaan terakhir terhadap bendakerja telah dihasilkan. Dari pemerhatian, kuprum tungsten adalah yang paling sesuai untuk digunakan sebagai elektrod dalam pemesinan WC-Co. Pemesinan yang lebih baik di nilai secara umumnya, dengan elektrod sebagai katod dan bendakerja sebagai anod. Dalam proses pemesinan ini, kajian dibuat terhadap pengaruh parameter mesin seperti arus elektrik, voltan, masa hidup denyutan,dan masa mati denyutan. Kualiti permukaan yang di kaji dalam eksperimen ini ialah kekasaran permukaan dan diukur dengan menggunakan mesin Perthometer. Kadar pembuangan material (MRR) dan nisbah kehausan elektrod (EW), telah dikira dengan menggunakan formula matematik. Keputusan eksperimen ini telah dikutip dan dianalisis secara statistik menggunakan perisian STATISTICA. Analisis ini telah dilakukan dengan menggunakan teknik Rekabentuk Eksperimen (DOE) dan teknik analisa variasi (ANOVA). Analisis in bertujuan untuk memilih keadaan pemesinan optimum untuk dilanjutkan ke ujian pengesahan. Ujian pengesahan ini bertujuan untuk menilai ralat marjin antara keputusan yang diramal oleh perisisian dengan keputusan ujian pengesahan melalui eksperimen dari segi hasil pemesinan.

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%	Percent
Ø	Diameter
t_i	Pulse time
t_0	Pause time
µ	Micron
s	Second
m	Minute
mm	milimeter
N	Newton
A	Ampere
V	Volt
I	Intensity
^oC	Degree Celsius
g	Gram
t	Time machining
W_b	Weight of workpiece before machining
Wa	Weight of workpiece after machining
α	Alpha base

LIST OF ABBREVIATIONS

EDM	Electrical Discharge Machining
CNC	Computer Numerical Control
R_a	Surface Roughness
EW	Electrode Wear
MRR	Material removal rate
WC	Tungsten Carbide
WC-Co	Tungsten Carbide with Cobalt content
CuW	Copper Tungsten
ANOVA	Analysis of Variance
DOE	Design of Experiment
SS	Statistical Significant
EWW	Weight of electrode used
WRW	Weight of workpiece used
HRB	Hardness Rockwell unit for soft steels
HRC	Hardness Rockwell unit for steel
CLA	Centre Line Average
AA	Arithmetic Average

CHAPTER 1

INTRODUCTION

1.1 Project background

Electrical discharge machining (EDM) is a non-traditional manufacturing process based on removing material from a part by means of a series of repeated electrical discharges(created by electric pulse generators at short intervals) between a tool, called electrode, and the part being machined in the presence of a dielectric fluid [1]. At the present time, EDM is a widespread technique used in industry for high-precision machining of all types of conductive materials such as metals, metallic alloys, graphite, or even some ceramic materials.

The adequate selection of manufacturing conditions is one of the most important aspects to take into consideration in the die-sinking electrical discharge machining (EDM) of conductive steel, as these conditions are the ones that are to determine such important characteristics as: surface roughness, electrode wear (EW) and material removal rate (MRR).In this research, a study will be perform on the influence of the factors of peak current, pulse on time,interval time and power supply voltage over the listed technological characteristics.

The material used in this study is a tungsten carbide or hard metal such as WC–15%Co. Approximately 50% of all carbide production is used for machining applications but tungsten carbides are also being increasingly used for non-machining applications, such as mining,oil and gas drilling, metal forming and forestry tools.[7]

Accordingly, mathematical models will be obtained using design of experiments(DOE) to select the optimal machining conditions for machining WC-Co using EDM.

1.2 Problem statement

In EDM, the selection of parameters play a main role in producing good surface quality,high material removal rate and less electrode wear. This research aim is to investigate the proper selection of parameters in EDM for machining hardened material and studies these selected different parameters which are able to deliver better results in terms of surface quality of tungsten carbide(WC), material removal rate and electrode wear. The problem might be interfere the result in this experiment when the selection of the parameters are not suitable and unproper to investigate on these machining characteristics.

1.3 Objectives of project

1) To evaluate the performance of EDM on tungsten carbide(WC) with respect to various responses such as surface quality,electrode wear(EW) and material removal rate(MRR)
2) To establish mathematical model for all responses involved which are surface quality,material removal rate(MRR) and electrode wear(EW).
3) Full factorial method from design of experiment(DOE) used in order to analyze and determine global solutions for optimal cutting parameters of EDM operation.

1.4 Project Scopes

1) Sodick AQ55L EDM Die-Sinking CNC machine is used for this research.
2) Machining tungsten carbide with 15% cobalt content that is WC with copper tungsten as electrode using EDM machines.
3) Parameters to be studied includes pulse on time,interval time,peak current and power supply voltage.

4) Surface quality to be investigate is surface roughness using Perthometer machine.
5) MRR and Electrode Wear will be calculate using mathematical formula.
6) The classical design of experiment(DOE) and ANOVA method will be processed using STATISTICA software.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction of Electro Discharge Machining (EDM)

Electro Discharge Macihining or EDM is a machining method primarily used for hard metals or those that would be impossible to machine with traditional techniques. One critical limitation, however, is that EDM only works with materials that are electrically conductive. EDM or Electrical Discharge Machining, is especially well-suited for cutting intricate contours or delicate cavities that would be difficult to produce with a grinder, an end mill or other cutting tools. Metals that can be machined with EDM include hastalloy, hardened tool-steel, titanium, carbide, inconel and kovar.[1]

EDM is sometimes called "spark machining" because it removes metal by producing a rapid series of repetitive electrical discharges. These electrical discharges are passed between an electrode and the piece of metal being machined. The small amount of material that is removed from the workpiece is flushed away with a continuously flowing fluid. The repetitive discharges create a set of successively deeper craters in the work piece until the final shape is produced.[1]

2.2 Electrical Discharge Machining (EDM) - Die Sink

Electrical Discharge Machining (EDM) - Die Sink is one of the most extensively used non-conventional material removal processes. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage in the manufacture of mould, die, automotive, aerospace and surgical components. In addition, EDM does not make direct contact between the electrode and the workpiece eliminating mechanical stresses, chatter and vibration problems during machining.[2]

2.3 Operation of Electro Discharge Machining (EDM)

EDM is a thermo-electrical material removal process, in which the tool electrode shape is reproduced mirror wise into a work material, with the shape of the electrode defining the area in which the spark erosion will occur. As shown on Figure 2.2(a) and figure 2.2(b), the EDM is accomplished with a system comprising two major components:[2]

1)Machine tool
2)Power supply

The machine tool holds a shaped electrode, which advances into the work material and produces a high frequency series of electrical spark discharges. The sparks are generated by a pulse generator, between the tool electrode and the work material, submerged in a liquid dielectric, leading to metal removal from the work material by thermal erosion or vaporization.[2]

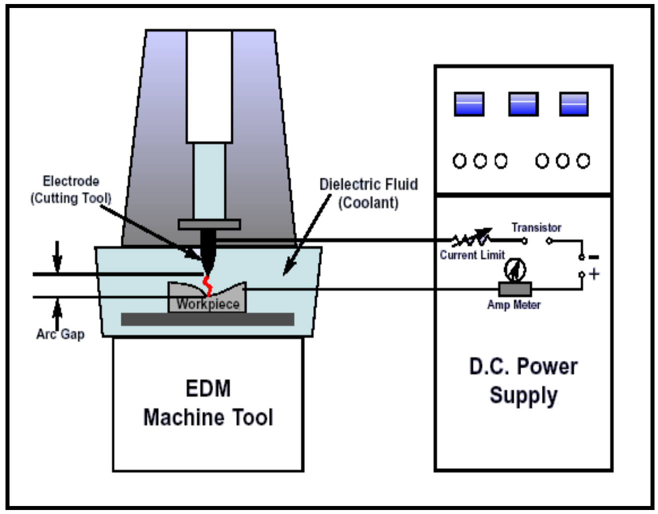

Figure 2.1(a)

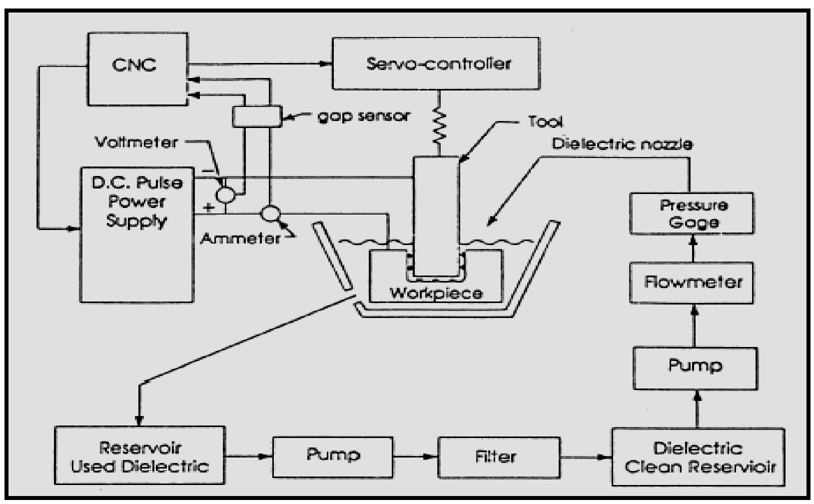

Figure 2.1(b)

Figure 2.1 (a) is the illustration and figure 2.1 (b) is schematic of basic EDM System.[2]

2.4 Machining parameters in EDM

Based on Yussni (2008), the variables parameters are have great effects to the machining performances results especially to the material removal rate (MRR), electrode wear rate and surface quality. There are two major groups of parameters that have been discovered and categorized[2]:

1) Non-electrical Parameters

   a. Injection flushing pressure
   b. Rotational of speed electrode

2) Electrical Parameters

   a. Peak current
   b. Polarity
   c. Pulse duration
   d. Power supply voltage

In the other hand, Van Tri (2002) categorized the parameters into five groups:[5]

1) Dielectric fluid; type of dielectric, temperature, pressure, flushing system
2) Machine characteristics; servo system and stability stiffness, thermal stability and accuracy
3) Tool; material, shape, accuracy
4) Workpiece
5) Adjustable parameters; discharge current, gap voltage, pulse duration, polarity, charge frequency, capacitance and tool materials

Some of the most important parameters implicated in the EDM manufacturing process are the following ones[2]:

1) On-time (pulse time or t_i):

The duration of time (μs) the current is allowed to flow per cycle. Material removal 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.

2) Off-time (pause time or t_0):

It is the duration of time (μs) between the sparks (that is to say, on-time). This time allows the molten material to solidify and to be wash out of the arc gap. This parameter is to affect the speed and the stability of the cut. Thus, if the off-time is too short, it will cause sparks to be unstable.

3) Arc gap (or gap):

It is the distance between the electrode and the part during the process of EDM. It may be called as spark gap.

4) Duty cycle :

It is a percentage of the on-time relative to the total cycle time. This parameter is calculated by dividing the on-time by the total cycle time (on-time plus off-time). The result is multiplied by 100 for the percentage of efficiency or the so called duty cycle.

5) Intensity (I):

It points out he different levels of power that can be supplied by the generator of the EDM machine. (*I*) represents the mean value of the discharge current intensity.

2.4.1 Electrode

EDM electrode materials and components consist of highly conductive and/or arc erosion-resistant materials such as graphite, copper or copper graphite. EDM is an acronym for electric discharge machining, a process that uses a controlled electrical spark to erode metal. EDM electrode materials include components made from brass, copper and copper alloys, graphite, molybdenum, silver, and silver tungsten.

EDM electrodes are manufactured in variety of forms such as coated wire, tube shaped, or bar stock, depending on the EDM electrode materials used and the application. A brass electrode is easy to machine and can also be die cast or extruded for use in special applications. However, brass is not as wear-resistant as other EDM electrode materials, such as copper or tungsten, so it is typically used to make EDM wire. Copper is a common base material because it is highly conductive and strong. A copper tungsten electrode is used in resistance welding electrodes and in circuit breakers. A copper zirconium diboride electrode is similar to a copper tungsten electrode, but has much higher erosion resistance and is more expensive to produce. A tellurium copper electrode is easy to machine and is useful in applications that require an electrode with a fine finish.

Other EDM electrode materials include graphite, silver, and molybdenum. A metal graphite electrode is the most common type of EDM electrode because it is easily machined, has high wear resistance and operating temperature capabilities, and is cost effective. A molybdenum electrode is typically used for special applications, such as small electrodes or EDM wire designed for high strength and arc erosion resistance. Silver is a highly conductive metal, and is used in conjunction with other EDM electrode materials such as erosion-resistant tungsten to make EDM electrodes for special applications.

A silver tungsten electrode may be used in deep slot applications that function under poor flushing conditions. Tungsten has a high melting point, which makes it a useful EDM electrode material in combination with more conductive metals. A tungsten carbide electrode is a combination of tungsten and carbon bound together with a metal binder. Tungsten carbide and other metal carbides are used for EDM electrode materials because they have high hardness qualities and are wear-resistant.

2.4.2 Flushing

Flushing is important because it removes eroded particles from the gap for efficient cutting. Flushing also enables fresh dielectric oil flow into the gap and cools both the electrode and the workpiece. Improper flushing causes erratic cutting, thus prevents the electrode from cutting efficiently. It is then necessary to remove the attached particles by cleaning the workpiece. Dielectric fluid is used as flushing to assist in the removal process of particles from the work area hence giving better surface finish [9].

There are five types of flushing fluid that usually use in system in EDM ;[10]. Two of the types of flushing are;

1) Pressure flushing

a. Through electrode

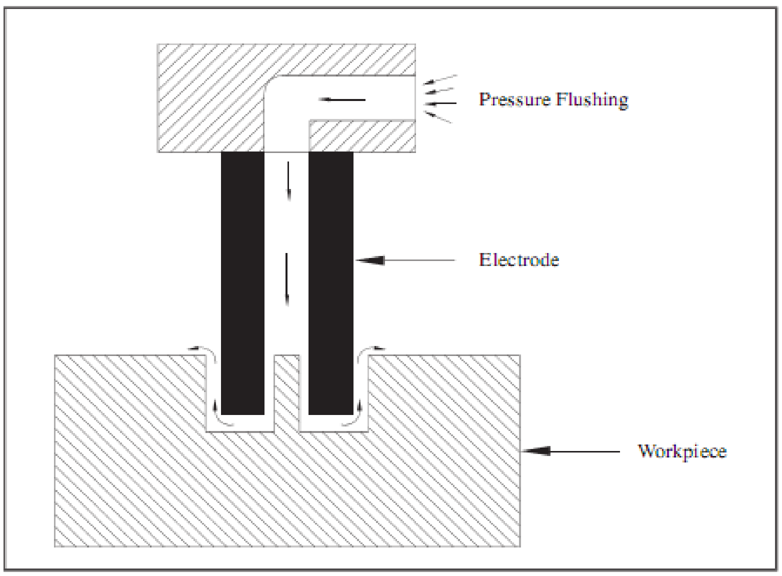

Figure 2.2 : Pressure flushing through electrode

b. Through workpiece

Pressure flushing also can be done by forcing the dielectric fluid through a workpiece mounted over a flushing pot. See figure . This method eliminates the need for holes in the electrode.

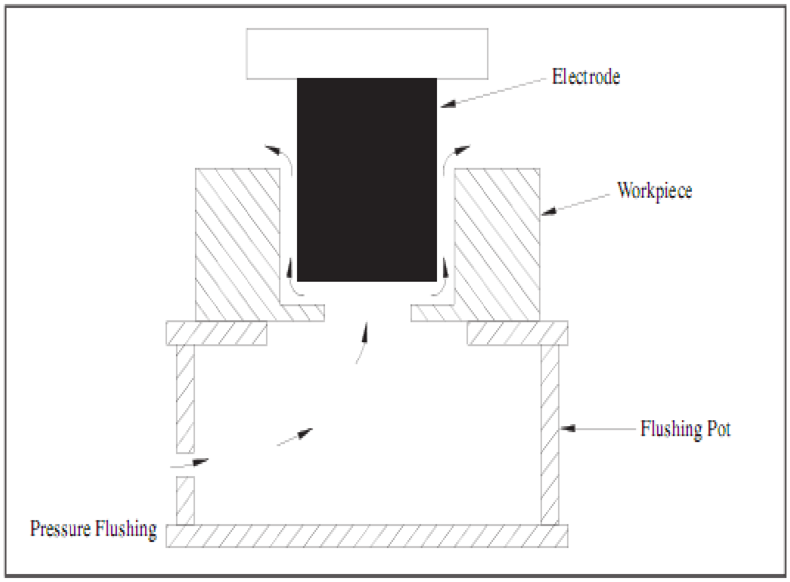

Figure 2.3 : Pressure flushing through workpiece

3) Jet flushing

Jet or side flushing is done by tubes or flushing nozzle which direct the dielectric fluid into gap,as shown in figure 2.4

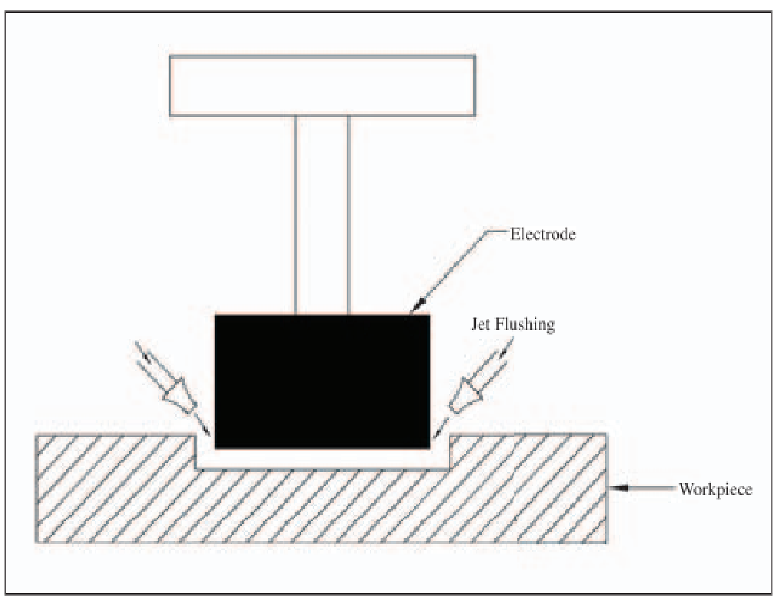

Figure 2.4 : Jet flushing using multiple flushing nozzle

2.4.3 Dielectric fluid

Basic characteristics required for dielectric used in EDM are high dielectric strength and quick recovery after breakdown [9].
Dielectric fluid performs three important functions [10];
1) The fluid forms a dielectric barrier for the spark between the workpiece and the electrode
2) The fluid cools the eroded particles between the workpiece and the electrode
3) The pressurized fluid flushes out the eroded gap particles and remove the particles from the fluid by causing the fluid to pass through a filter system.

Most dielectric media are hydrocarbon compounds and water. The hydrocarbon compounds are in the form of refined oil,better known as kerosene. While the fluid properties are essential, the correct fluid circulating methodology is also important. The selection of suitable dielectric is based on the type of materials and the processes that are used. The performance of the dielectric may vary from one workpiece to another.[10]

2.5 Machining Characteristics

EDM performance, regardless of the type of the electrode material and dielectric fluid, is measured usually by the following criteria:

1) Metal removal rate (MRR)
2) Resistance to wear or electrode wear (EW)
3) Surface Roughness (R_a) of workpiece

2.5.1 Material removal rate

The following equation is used to determine the MRR value ;

$$\text{MRR} = \frac{Wa - Wb}{t} \text{ (g/min)} \tag{2.1}$$

where:

W_b = weight of workpiece material before machining (g)

W_a = weight of workpiece material after machining (g)

t_m = machining times (min)

This method is also adopted by Puertas and Perez (2003) and Puertas et al.(2004), and many other researchers. Maximum of MRR is an important indicator of the efficiency and cost effectiveness of the EDM process, however increasing MRR is not always desirable for all applications since this may scarify the surface integrity of the workpiece. A rough surface finish is the outcome of fast removal rates.[6]

2.5.2 Electrode wear

Electrode wear is a deformation of the tip face over time due to the resistance welding process. Based on Mr. Mohd Yussni Bin Yaakob(2008),from the the electrode heating and force during the resistance welding process cause the surface area of the tip face to deform over time. The surface area increase causes the current density (amps/unit area) to decrease, potentially reducing the weld size. (The current density can be increased by using a current stepper.)

Proper knowledge of electrode wear is essential for determining the electrode size and number of electrodes. This also governs the economics of the EDM process. Basically, the electrode wear is a function of such factor as polarity, melting point of electrode, duration and intensity of spark discharges and the type of work material used in relation to the tool material.

The versatility of modern pulse generator has permitted a significant reduction in electrode wear. Through proper adjustment of such parameters like duration, intensity (roughing or finishing) with due respect to the size and nature work, electrode wear can be considerably reduced. Limited wear or the so called “no wear” EDM operations are possible using graphite electrodes and pulse generator.

The electrode wear also depends on the dielectric flow in the machining zone. If the flow is too turbulent, it results in an increase in electrode wear. Pulsed injection of the dielectric has enable reduction of wear due to dielectric flow.[2]

In term of the EWR value, the equation below is usually used;

$$\mathrm{EWR} = \frac{EWW}{WRW} \times 100\% \qquad (2.2)$$

where:

EWW = weight of electrode used (g)

WRW = weight of workpiece used (g)

The concept of electrode wear rate (EWR) can also be defined in many different ways, and in this study the EWR is defined according to the ratio in weight of the electrode and the workpiece, as this definition is the most commonly used among the researchers[6][7].

Minimum value of EWR always becomes an objective in many studies, where it indicates a minimum change in the shape of electrode, which lead to the better accuracy in the product. In EDM operation, it is quite natural that the cavity formed by an electrode is always bigger than the electrode size. Two aspects of dimensional accuracy of the drilled holes are involved such as diameter of the drilled hole and the diametrical taper over the hole depth.[6]

2.5.3 Surface roughness (surface quality)

Surface roughness also known as surface texture are terms used to describe the general quality of machined surface, which is concerned with the geometric irregularities and the quality of a surface. According to Armarego and Brown (1969), ideal surface roughness may be specified in various ways, but two common methods are the peak to valley height (h) and the arithmetic average, Ra (μm). The Ra value, also known as centre line average (CLA) and arithmetic average (AA) is obtained by averaging the height of the surface above and below the centre line.[16]

The surface produced by EDM process consists of a large number of craters that are formed from the discharge energy. The quality of surface mainly depends upon the energy per spark. If the energy content is high, deeper craters will 22 be attained, leading to poor surface. The surface roughness has also been found to be inversely proportional to the frequency of discharge .Assuming that each spark leads to a spherical crater formation on the surface of workpiece, the volume of metal removed per crater will be proportional to the cube of the crater depth.[15]

2.6 Tungsten carbide

Based on the Mikael Christensen and Göran Wahnström(2005), Tungsten carbide,with 15% cobalt content are a class of hard composite materials of great technological importance. They are widely used as tool materials in a large variety of applications where the demands on hardness and toughness are high, including such as mining, turning, cutting and milling.[3]

The microstructure of the material consists of a hard WC grain skeleton embedded in a tough metal binder phase. The internal surfaces, grain boundary and heterophase interfaces, determine to a large extent processes and properties of the material. Extensive ab-initio based calculations have therefore been performed in order to assess the strength and stability of interfaces in cemented carbides and to analyze these properties in terms of the electronic structure.Compressive strength rises with decreasing binder content and smaller grain size. A carbide grade with a small WC grain size and a low binder content has a typical compressive strength approaching 7.000 N/mm2.

WC-Co is reduced at elevated temperatures. This drop in strength becomes more significant at temperatures above 600^{o} C. For use at elevated temperatures, grades with cubic carbides and or alloyed binder are recommended..The main properties used to characterizes, the mechanical properties of cemented carbide are hardness, transverse rupture strength and fracture toughness.[4]

2.7 Full Factorial Design

The full factorial designs are among the most widely DOE used for product, process design and process improvement. The capability to estimate the correlation between two or more factor in one time is the one of the advantages when used Full Factorial design method. In addition, this method also can identify the importance factors in the experiment under variety of conditions without sacrifices any factors.

The very simple type of factorial design is a two-factor experiment, which is the effect of two factors on one or more response variables are tested all together. It is commonly use two level design for each factor study, where k is the number of combinations will be 2^k. The two level design can only yield information on the edges and by doing so, it provides simple linear model that accounts for all possible parameter relations.

2.7.1 Design of experiment

Design of experiment (DOE) is a test or series of tests in which purposeful changes are made to the input variables of a process or system so that the reasons for change in the output responses can be observed and identified [14]. This method has found broad application in many disciplines. Experimental 33 design methods also play a major role in engineering design activities [13], where new products are developed and existing ones needed improvement. Some applications of experimental design in engineering design include [12];

1) Evaluation and comparison of basic design configuration
2) Evaluation of material alternatives
3) Selection of design parameters so that the product will work well under a wide variety of field conditions
4) Determination of key product design parameters that impact product performance.

Applying DOE to monitor the process characteristics in EDM is very much appropriate, since it provides the best setting of EDM parameters to fulfill the multi objectives.

2.8 Test for significance of the regression model (ANOVA)

The test for the significance of the regression model is performed as an analysis of variance (ANOVA) procedure by calculating the ratio between the regression sum of squares and error sum of squares and comparing the result to the F-ratio with the appropriate degrees of freedom at a given significance level. The F-ratio, also called variance ratio, is the ratio of variance due to the effect of a factor, in this case the model, and variance due to the error term. This ratio is used to measure the significance of the model under investigation with respect to the variance of all the terms included in the error term at desired significance level, α[11].

Usually, significance levels α of 0.10, 0.05, and 0.01 are used to determine the value of F-ratio to indicate a significant model as desired. An ANOVA table is commonly used to summarize the test of significance of the model. There are variations in the lay out of this table.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this project include many process such as preparation on tool and workpiece,set up experiment and running the experiment. Those processes wil be described in this chapter according to the flow chart. In this chapter,every data and information were gathered together snd being analyzed according to the objectives and scope of this project. Proper experimental plan is necessary to achieve good results in conducting research.

In this chapter will describe about overall progress from the beginning until the end of this project. There are four main processes involve in this project that starts with experimental, collecting the data, analyze the result and lastly confirmation test. As shown before in the Gantt chart and flow chart, this chapter will explain more detail about the processes above.

In this chapter all the equipments used in this research are described which include the measurement equipments. A summary of the research flowchart is shown in Figure 3.2.

Various kind of equipments will be used in this research for determining the influence of EDM parameters on surface quality, MRR and EW of WC–Co.

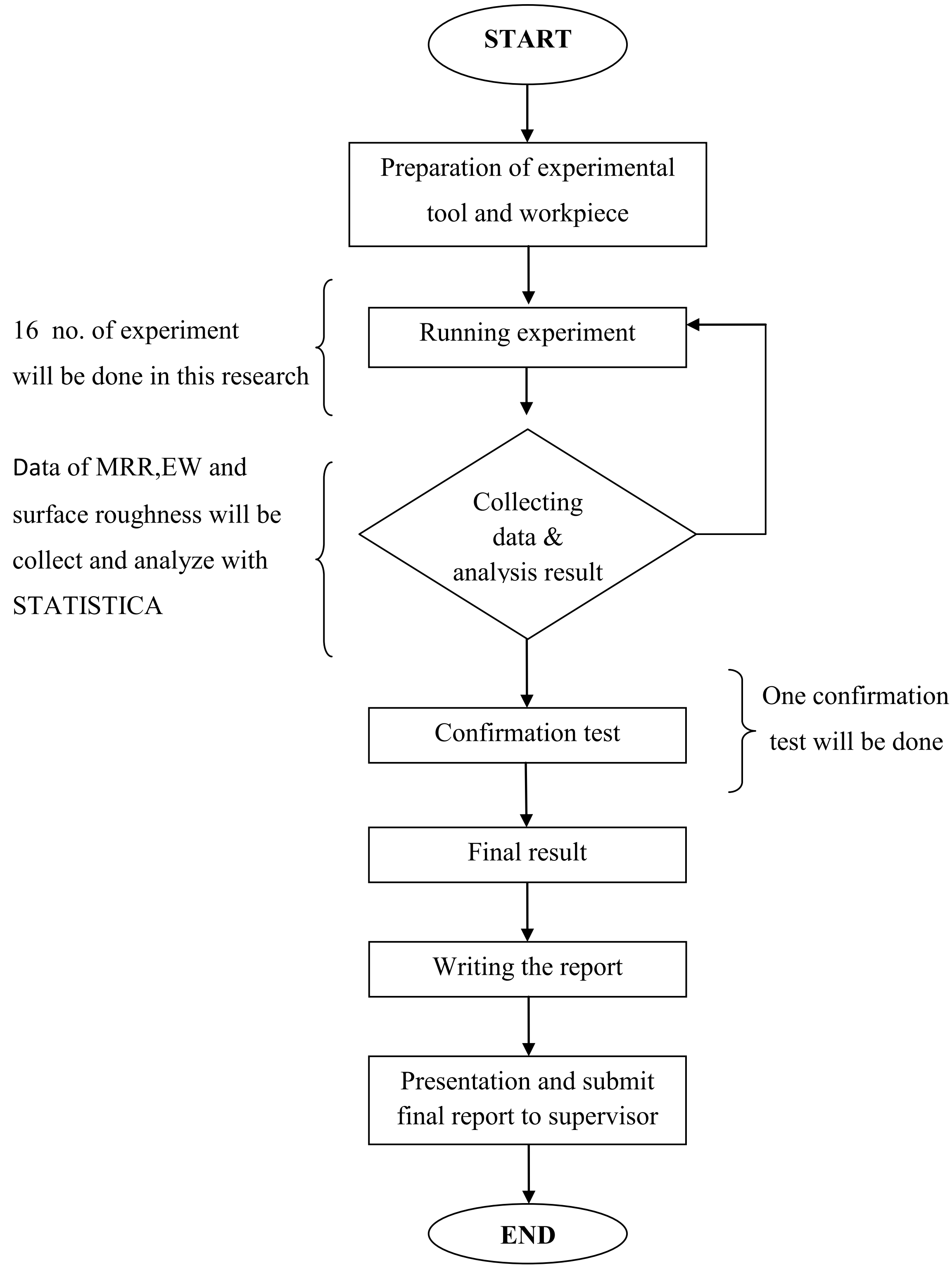

Figure 3.0 : Flow chart of methodology

3.3 Research Design Variables

The design variables are described into two main groups, which are response parameters and machining parameters.

3.3.1 Response Parameters

The response parameters include:

1) Material removal rate (MRR)
2) Electrode wear rate (EWR)
3) Surface Roughness (R_a)

3.3.2 Machining Parameters

The parameters that are involved in this study are shown in Table 3.1

Table 3.1 Machining Parameters

Variables	**Set-up**
Workpiece	Tungsten Carbide,WC-15Co Block size : (100mm x 80mm x 10mm)
Tool Electrode	Copper Tungsten(CuW) (Ø 8 mm)
Depth of cut	0.5 mm
Dielectric Fluid	Kerosene
Flushing	On(jet flushing)
Research Parameters	**Set-up**
Peak Current (A)	7 – 10
Pulse on Time (µs)	5 – 8
Pulse off Time (µs)	5 – 10
Power supply voltage (V)	11 – 22

3.3.3 Workpiece Material

The workpiece material used in project is a WC–15Co, which means that it has a proportion of cobalt of 15%.

Table 3.2 Workpiece material properties[8]

Cemented carbide	Room temp. hardness, HV	Modulus of elasticity, GPa	Transverse rupture strength, MPa	Coefficient of thermal expansion, 10^{-6}/K	Thermal conducti-vity, W/m•K	Density, g/cm^3
WC-20 wt% Co	1050	490	2850	6.4	100	13.55
WC-10wt% Co	1625	580	2280	5.5	110	14.50
WC-3 wt% Co	1900	673	1600	5.0	110	15.25
WC-10 wt% Co-22 wt% (Ti, Ta, Nb)C	1500	510	2000	6.1	40	11.40

3.3.4 Electrode Material

In this study,copper tungsten will be used as an electrode material. This copper tungsten(CuW) rod had 8 mm of diameter.

Table 3.3 Electrode material properties

Specification	**Value**
Density(g/cm^3)	15.2
Specific resistance (μΩ/Cm)	5.5
Coefficient of expansion/^{o}C	5 x 10-4
Composition	75% Tungsten, 25% Copper
Hardness	94 HRB, 18 HRC

3.4 Major equipment

The following equipments that will be used in this experimental works:

1) CNC EDM die sink (Figure 3.1)

Brand : Sodick CNC EDM die sink

Model : AQ55L

No of axis : 3 axes (X, Y & Z)

This machine will be used to drill hole on the WC-Co for conducting the electrical discharge machining process in hole making.

Figure 3.1 Sodick CNC EDM die sink

2) Surface roughness tester (Figure 3.2)

Brand : Mahrsurf XR 20

Model : Perthometer

Surface roughness of the machined workpieces will be measured by using this machine.

Figure 3.2: Surface roughness tester

3) Balance (Figure 3.3)

Brand : Precisa

Model : 92SM – 202A DR

Resolution : 10 nanogram

Precision balance is purpose to measure the weigh of the workpiece and electrode before ands after the machining process.

Figure 3.3: Balance Machine

4) STATISTICA Software

This software is purpose for planning experimental design matrix and analyzing all the responses according to statistical method.

3.5 Response parameters measurement

3.5.1 Material Removal Rate (MRR)

The MRR of the workpiece will be measure by dividing the weight of workpiece before and after machining (found by weighing method using balance) againts the machining time that was achieved. After completion of each machining process, the workpiece was blown by compressed air using air gun to ensure no debris and dielectric were present. A precise balance (Precisa 92SM – 202A DR) will be use to measure the weight of the workpiece required.

The following equation is used to determine the MRR value ;

$$\text{MRR} = \frac{Wa - Wb}{t} \text{ (g/min)} \qquad (2.1)$$

where:

W_b = weight of workpiece material before machining (g)

W_a = weight of workpiece material after machining (g)

t_m = machining times (min)

3.5.2 Electrode Wear (EW)

The concept of EW can be defined in many ways, the present study define the EW according to ratio in weight of the electrode and the workpiece where expressed as percentage. Similar procedure for measuring the weight of workpiece will be used to determine the weight of the electrode before and after machining.

The following equation is used for determine the EW value:

$$EW = \frac{EWW}{WRW} \times 100\% \tag{2.2}$$

where:

EWW = weight of electrode used (g)

WRW = weight of workpiece used (g)

3.5.3 Surface Roughness (R_a)

There are various methods available for measuring the surface roughness of the workpiece. The arithmetic surface roughness value (R_a) will be adopted and measurements will be carry out at the bottom and at the side wall of the holes using a Mahrsurf XR 20 Perthometer.

3.6 Experimental plan

The experimental in this research will involve four factors which are varied at two levels; high and low levels. The four factors are Voltage, Current, Pulse on time, and Interval time . They are labeled A, B, C and D respectively. The details of the factors for the research are given in Table 3.4

Table 3.4 Table of research parameters and their levels

Factors	**Name**	**Units**	**Type**	**Low level (-1)**	**High level (+1)**
A	Voltage	Volt	Numerical	80	100
B	Current	Ampere	Numerical	8	24
C	Pulse on time	µs	Numerical	12	50
D	Interval time	µs	Numerical	12	50

The experiment will run using full factorial design. This design is purpose to identify the significant factors that effect the machining responses. The results were then used for the experimental plan in this research. Experimental plan table is given in table 3.5

Table 3.5 Factors and levels for experiment design with full factorial design

No. Of Experiment	A: Voltage (Volt)	B: Peak Current (A)	C: Pulse on Time (µs)	D:Interval Time (µs)
1	11	7	5	5
2	11	7	5	10
3	11	7	8	5
4	11	7	8	10
5	11	10	5	5
6	11	10	5	10
7	11	10	8	5
8	11	10	8	10
9	22	7	5	5
10	22	7	5	10
11	22	7	8	5
12	22	7	8	10
13	22	10	5	5
14	22	10	5	10
15	22	10	8	5
16	22	10	8	10

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the experimental results on EDM machining of different paramaters of the tungsten carbide with 15% cobalt content that is WC with copper tungsten as electrode using EDM machine. Parameters of EDM that were investigated in this experiment are Power supply voltage (V),Peak current (A), Pulse time (μs) and Interval time (μs). Analysis and conclusion are made on the surface roughness,material removal rate (MRR) and electrode wear (EW). The results are extracted from a series of experiment trials, based on the variation of machining parameters given in Table 3.1. The experimental plans for EDM process were based on the full factorial design. The data of the results of the experiment were analyze using STATISTICA software. Surface roughness were measured by Perthometer. MRR and EW were calculated by using mathematical formula.

The result are interpret base on the data, tables, and graft. The analysis consists of 3 main elements which are:

- i. Significant Effects
    - I. Surface Roughness (SR)
    - II. Material removal rate (MRR)
    - III. Electrode wear (EW)
- ii. Analysis of Variance (ANOVA)

iii. Estimated result at Optimum condition

These three elements will give us significance of each parameter to the performance of machining characteristics and their optimum condition.

Besides the results of the statistical analysis, the result of the confirmation test also is discussed in this chapter.

4.2 Experimental Results

The experimental plans and results for the series of machining test are presented in this section.

4.2.1 EDM of WC-Co

The experimental trials involved four factors which were varied at two levels; high and low levels. The four factors were Voltage, Peak Current, Pulse on time and Interval time. They are labeled A, B, C, D and E respectively. The details of the factors for the experiment are given in Table 4.1. The machining responses that were investigated were surface roughness, MRR, and EW.

Table 4.1 : Factors and levels for EDM of WC-Co

Factors	**Name**	**Units**	**Type**	**Low level (-1)**	**High level (+1)**
A	Voltage	Volt	Numerical	11	22
B	Peak Current	Ampere	Numerical	7	10
C	Pulse on time	µs	Numerical	5	8
D	Interval time	µs	Numerical	5	10

The EDM process was investigated using full factorial design. This design is used to identify the significant factors that effect the machining responses. The results were then used for the confirmation test to compare with predicted result. STATISTICA software version 7 was employed and the experimental plans are given in Table 4.2. The experimental results for the EDM of WC-Co are given in Table 4.3

Table 4.2 : Experimental plans for EDM of WC-Co

No. Of Experiment	**A: Voltage (Volt)**	**B: Peak Current (A)**	**C: Pulse on Time (µs)**	**D:Interval Time (µs)**
1	11	7	5	5
2	11	7	5	10
3	11	7	8	5
4	11	7	8	10
5	11	10	5	5
6	11	10	5	10
7	11	10	8	5
8	11	10	8	10
9	22	7	5	5
10	22	7	5	10
11	22	7	8	5
12	22	7	8	10
13	22	10	5	5
14	22	10	5	10
15	22	10	8	5
16	22	10	8	10

Table 4.3 : Experimental results for EDM of WC-Co

No of experiment	Surface roughness (µm)	Material removal rate (g/min)	Electrode wear (%)
1	1.5481	0.0117	55.5
2	1.775	0.01068	34.53
3	1.2861	0.0139	60.33
4	1.6135	0.009414	45.13
5	1.3724	0.01215	74.32
6	1.925	0.0111	62.92
7	1.4239	0.0125	63.61
8	1.917	0.009605	50.77
9	1.509	0.0209	58.64
10	1.9063	0.0198	34.65
11	1.958	0.008684	69.36
12	1.8659	0.00278	41.93
13	2.0243	0.0313	88.64
14	1.9371	0.0294	53.34
15	1.6085	0.0182	77.5
16	1.851	0.009142	69.39

The results from the Table 4.3 were then input to the STATISTICA software for further analysis according to the steps outlined for full factorial design. Without performing any transformation on the responses, the revealed design status was evaluated, and all the information was used for further analysis, following the steps outlined in Appendix C-3.

4.3 ANALYSIS ON SURFACE ROUGHNESS, R_a

4.3.1 Significant Effects

The significant of effect is important in determination of optimum condition. Table 4.4 gives the significant factor from this investigation. The parameters such voltage and pulse off time (red font) as the main effect which contributes more effect of surface roughness, R_a in machining process.

Factor	Effect Estimates; Var.:Surface roughness (μm); DV: Surface roughness (μm)					
	Effect	Std.Err.	t(11)	p	Coeff.	Std.Err. Coeff.
Mean/Interc.	1.720069	0.044214	38.90348	0.000000	1.720069	0.044214
(1)Voltage (V)	0.224888	0.088427	2.54319	0.027325	0.112444	0.044214
(2)Peak Current (A)	0.074663	0.088427	0.84434	0.416467	0.037331	0.044214
(3)Pulse on Time (μs)	-0.059162	0.088427	-0.66905	0.517259	-0.029581	0.044214
(4)Pulse off Time (μs)	0.257562	0.088427	2.91270	0.014121	0.128781	0.044214

Table 4.4: Significant factor of surface roughness

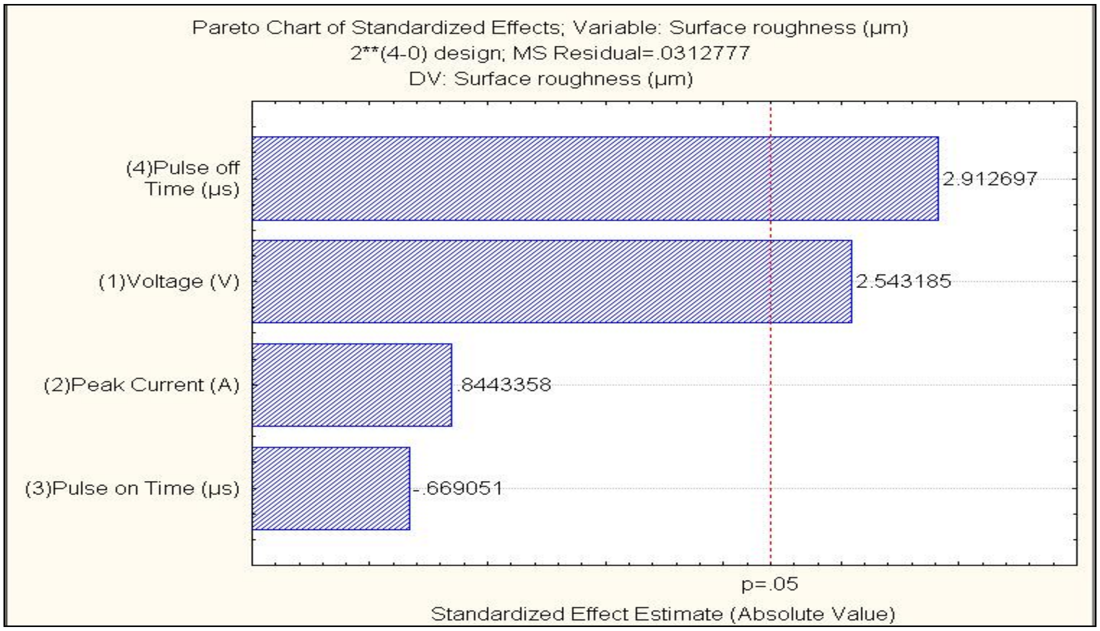

Figure 4.1: Pareto Chart of Standardized Effects; Variable: Surface Roughness, R_a.

From the Figure 4.1, shows the Pareto chart for the effects corresponding to to the R_a parameter. As can clearly seen, two of the bars of the diagram which go beyond the vertical line correspond to the effects which are statiscally significant,for a confidence level of 95%. Therefore, there are two significant effects which, in descending order of contribution, are the factor of pulse off time (interval time) and factor of voltage. Then followed by the peak current and pulse on time which these factors gave a small contribution of effect to the R_a parameter than the other two factors. These factors can be independent variables because it does not give the significant effect to the surface roughness.

The significant of main effects are determined where the p value $P<0.05$. The other factors and interaction factors which are not significant are $P>0.05$ and can discarded to produce a reduced model if desired. Their contribution to the variation then goes into error.

4.3.2 Surface roughness, R_a

All the results for R_a have been calculated and shown (in Table 4.3). According to Figure 4.2 show the higher Pulse Off time will be give the rougher surface of WC-Co. In addition, the R_a is increased with the increasing in pulse off time. Figure 4.3 shows that the result of the graph almost same with the result in Figure 4.2; when the voltage are increased the surface roughness will followed increased. Figure 4.4 shows that when the peak current is inrceased the surface roughness also increase but the effect is too small to the surface roughness.Other than that, the Figure 4.5 is different because when increasing the pulse on time will give the better R_a.

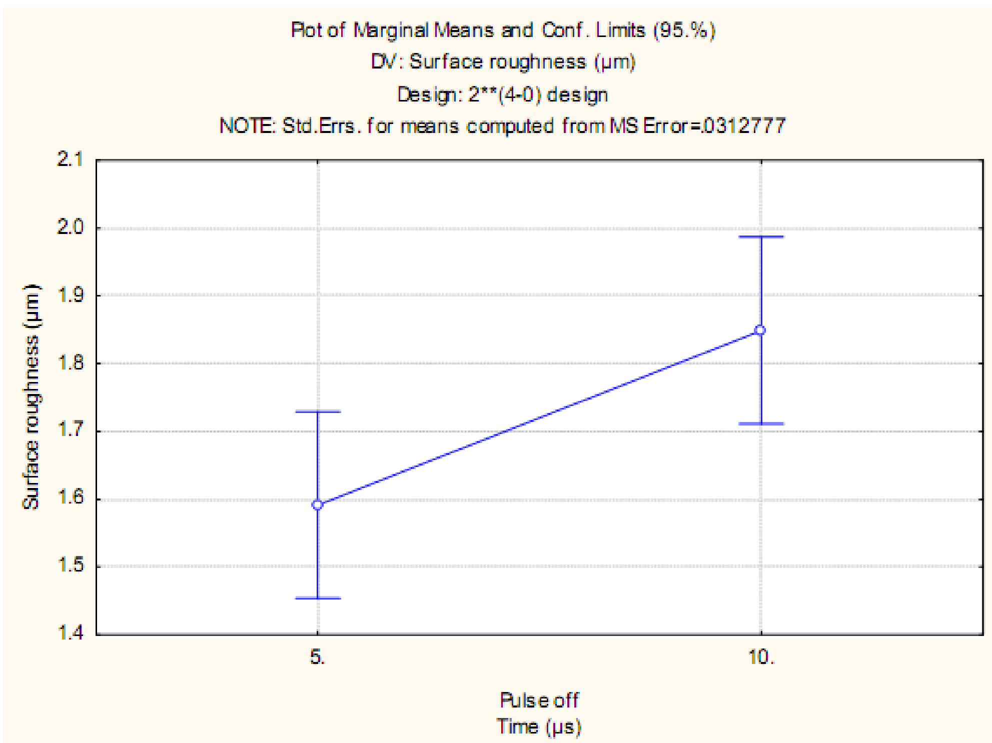

Figure 4.2: Graph of Surface Roughness, R_a versus Pulse off Time, (µs)

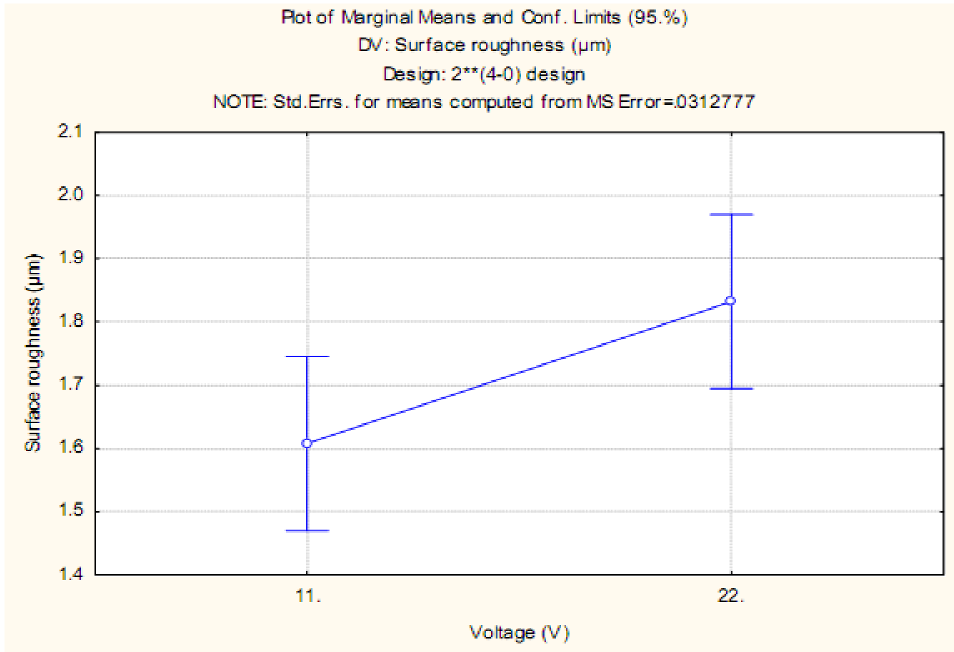

Figure 4.3: Graph of Surface Roughness, R_a versus Voltage (V).

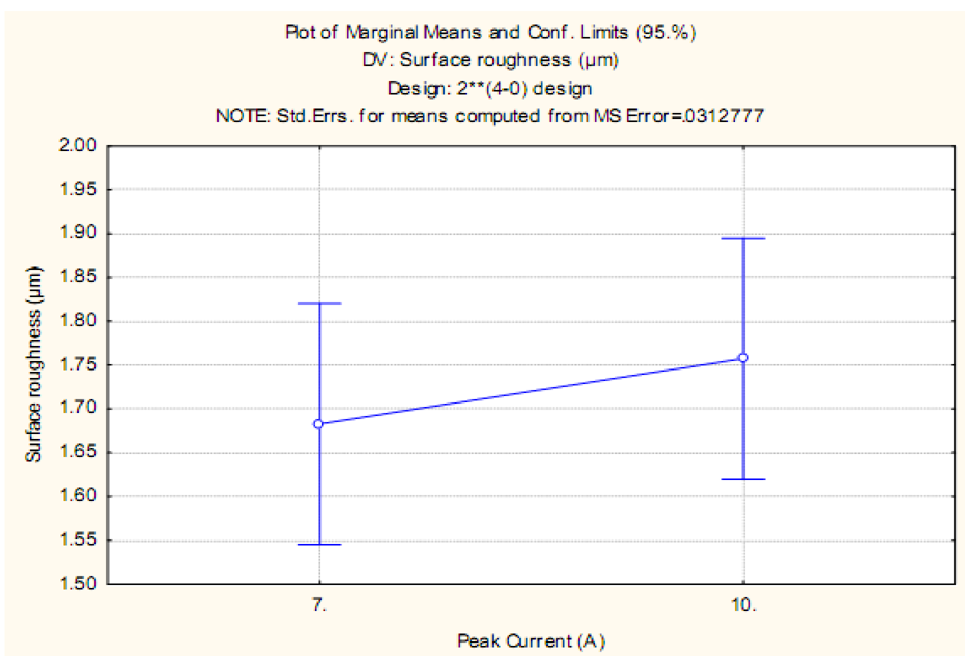

Figure 4.4: Graph of Surface Roughness, R_a versus Peak Current (A)

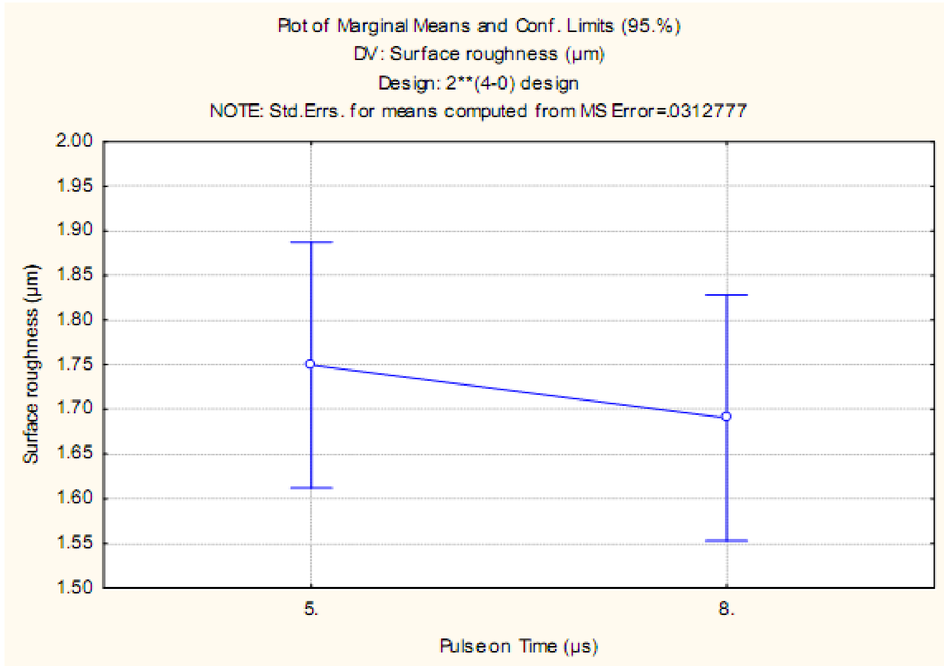

Figure 4.5: Graph of Surface Roughness, R_a, versus Pulse on Time (μs)

4.3.3 Analysis of Variance (ANOVA)

Using the STATISTICA software, ANOVA applied to the results of experiment to determine the percentage contribution of each factors. This information shows of the factors need to control and which do not.

According to the Table 4.5, there is degree of freedom that contributes error on result. The main factors that need to control or consider is pulse off time (μs) and voltage (V), (red font) where these factors shows high statistical significant, SS and has value of $P<0.05$.

Factor	ANOVA; Var.:Surface roughness (µm)				
	SS	df	MS	F	p
(1)Voltage (V)	0.202298	1	0.202298	6.467792	0.027325
(2)Peak Current (A)	0.022298	1	0.022298	0.712903	0.416467
(3)Pulse on Time (µs)	0.014001	1	0.014001	0.447629	0.517259
(4)Pulse off Time (µs)	0.265354	1	0.265354	8.483804	0.014121
Error	0.344055	11	0.031278		
Total SS	0.848005	15			

Table 4.5: The ANOVA effects of Ra with no interaction model

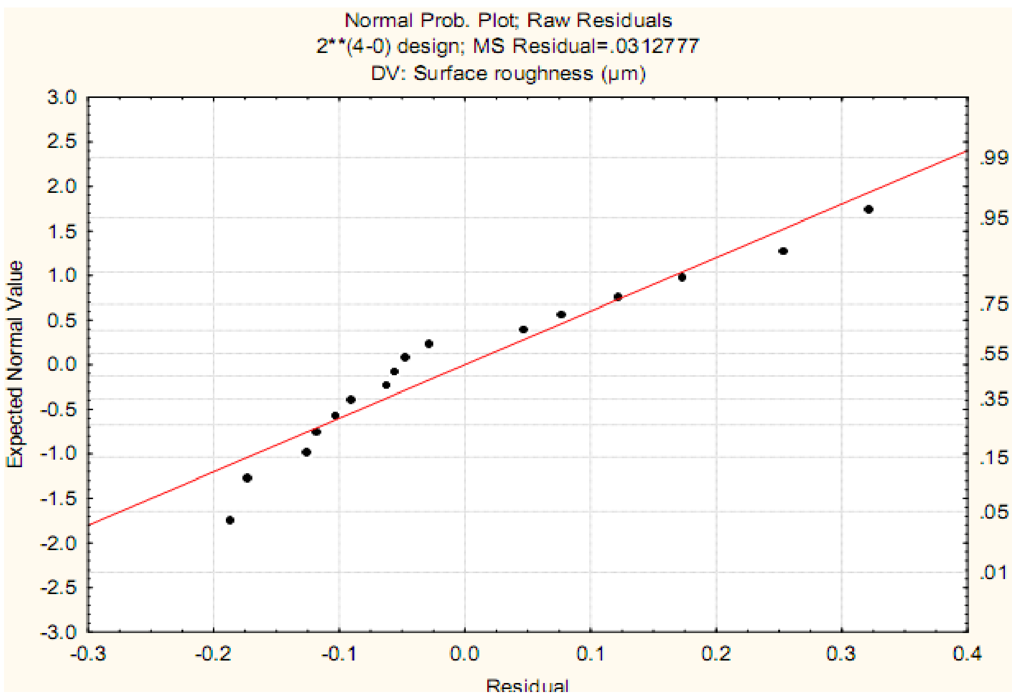

Figure 4.6 : Normal Probability Residual plot to Expected Normal Value of effect, R_a

From Figure 4.6 shows the normality of the distribution of a variable, which is extent the distribution of the variable follows the normal distribution. The graph shows the results are proportional between residual and the expected normal values. All effect fall to response and this is an important outcome because all setting gives result to surface roughness, R_a.

4.3.4 Estimate Result at Optimum Condition

From Figure 4.7 present a three-dimensional surface plot of the data for pulse on time = 5 (µs) and peak current = 7 A. Notice that the effect of the interaction between pulse off time, (µs) and voltage (V) in the data is "twist" plane, so that there is curvature in the response function to the surface roughness. If the data contain no interaction, the surface plot is a plane lying above the peak current and pulse on time.

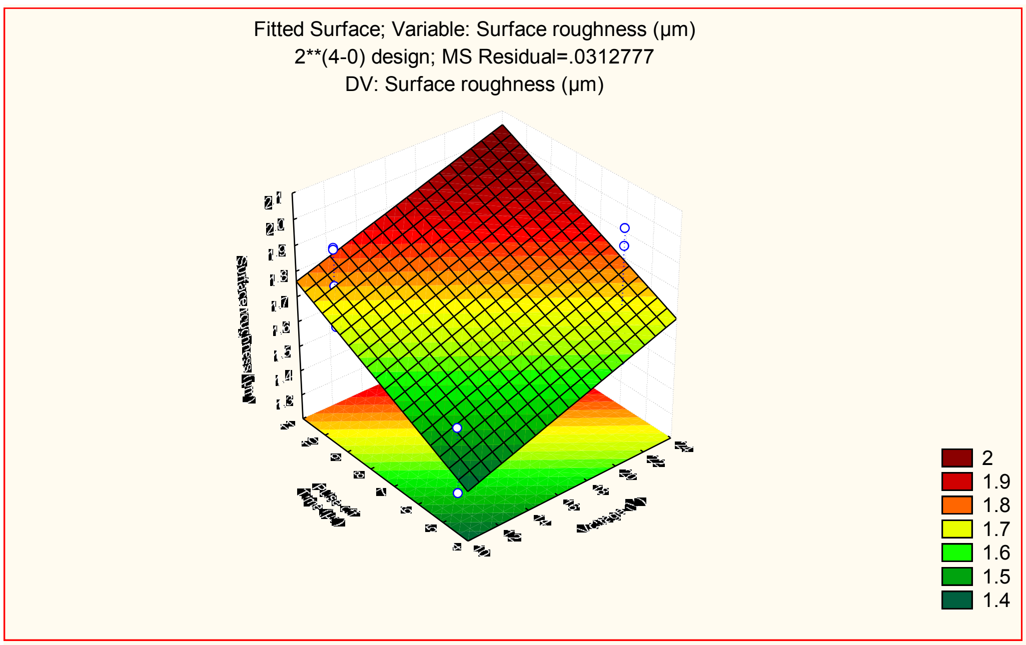

Figure 4.7: 3-D surface plots of the data main effects of the voltage and pulse off time.

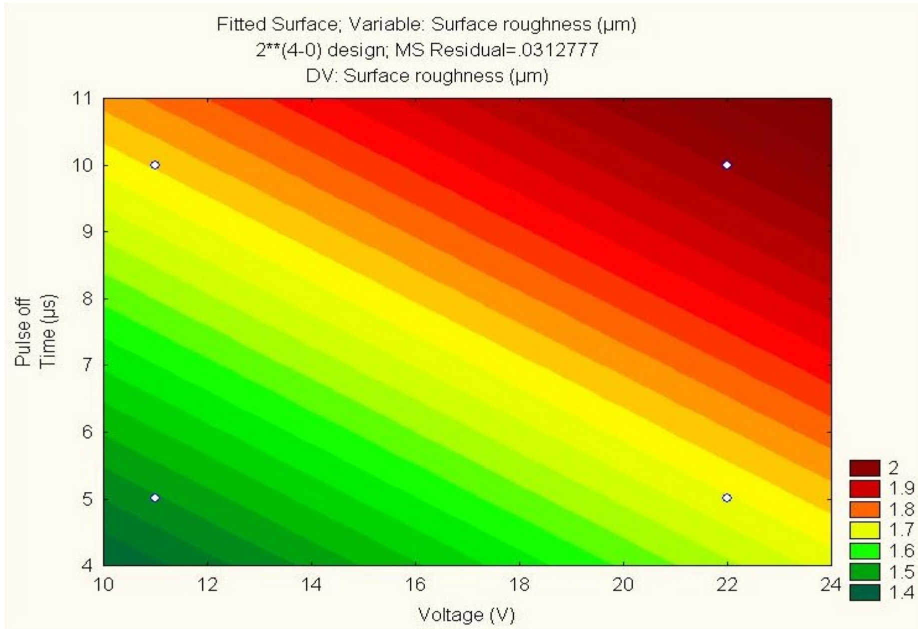

Figure 4.8: 2-D fitted surface distribution of effect between two factors.

Figure 4.8 shows the two –dimensional with the distribution effect of surface roughness where the data is same. The contour plot show that the red area is more higher value of surface roughness compare to the green and yellow area. From the contour plot, it shows that the higher value of pulse off time and voltage contribute rougher of WC-Co surface.

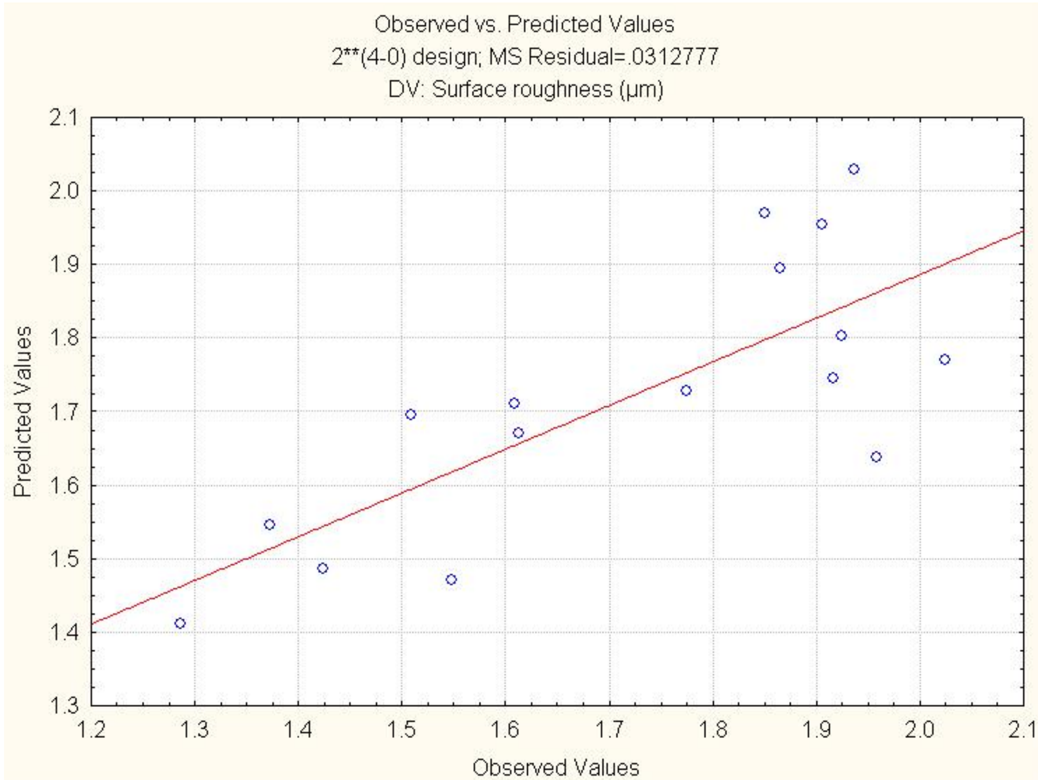

Figure 4.9: Observed Values versus Predicted Values plot of R_a

From Figure 4.9, observed-predicted values are linear and proportional. There is still having error because all the point on the linear line but the distribution is near the line. Overall result can be predicted based on the DOE methodology and STATISTICA software. The desired quality characteristics can be expressed in Table 4.6.

Table 4.6: Quality Characteristics of Machining Performance of R_a.

Machining Characteristics	Quality Characteristics
Pulse Off Time (µs)	The smaller the better
Voltage (V)	The smaller the better

The optimum parameter determined:-

i. Pulse Off Time= 5 µs
ii. Voltage, (V) = 11 V

4.3.5 Confirmation Test

The significant parameters are obtained, and the optimum result also identified, the confirmation test need to be carried out. This is to ensure the theoretically predicted for optimum result will not to vary out of order. The followings are confirmation test result and the predicted value of surface roughness from STATISTICA based on optimum value as shown in Table 4.7 and Table 4.8.

No. of trial	Surface Roughness (Ra) For confirmation test	
	1 Repeated Ra	2 Ra Average
1	1.527	
2	1.235	1.358
3	1.314	

Table 4.7: Confirmation test result of R_a

	Predicted Value; Var.:Surface roughness (µm)		
Factor	Regressn Coeff.	Value	Coeff. * Value
Constant	0.913035		
(1)Voltage (V)	0.020444	11.00000	0.224888
(2)Peak Current (A)	0.024888	7.00000	0.174213
(3)Pulse on Time (µs)	-0.019721	5.00000	-0.098604
(4)Pulse off Time (µs)	0.051512	5.00000	0.257562
Predicted			1.471094

Table 4.8: Predicted Value of R_a based on STATISTICA

4.3.6 Comparison Test

The comparison test between theoretically predicted and confirmation test results is a final consideration that will determine weather the optimum parameters predicted are in range. In this investigation, the range or sometimes called margin of error is set bellow than 10%. Margin of error is calculated as follows:

Error Margin (%) =
[{Predicted result- Confirmation test result} / Conformation test result] * 100

Table 4.9: Comparison test result of R_a

<table>
<tr><td rowspan="2"></td><td colspan="2">Optimal Machining Parameter</td><td rowspan="2">Error Margin (%)</td></tr>
<tr><td>Prediction (STATISTICA)</td><td>Experiment (confirmation test)</td></tr>
<tr><td>Setting level</td><td>Peak Current= 7A
Pulse On-time = 5 μs
Pulse OFF-time= 5μs
Voltage= 11V</td><td>Peak Current= 7A
Pulse On-time = 5 μs
Pulse OFF-time= 5μs
Voltage= 11V</td><td rowspan="2">8.32</td></tr>
<tr><td>Surface Roughness, μm</td><td>1.471</td><td>1.358</td></tr>
</table>

Table 4.9 show the comparison test between theoretically predicted and confirmation test result for differences set of data on the followings. From the table error margin is 8.32 % shows the result is inaccurate. However the result still can be accepted because the error is small. This indicates that DOE Full Factorial method can be used in order to determine optimum parameters.

4.4 ANALYSIS ON MATERIAL REMOVAL RATE, MRR

4.4.1 Significant effect

The significant of effect is important in determination of optimum condition. Table 4.10 gives the significant factor from this investigation. The parameters such pulse on time (red font) as the main effect which contributes more effect of Material removal rate, MRR in machining process.

Factor	Effect Estimates; Var.:Material removal rate (g/min); DV: Material removal rate (g/min)					
	Effect	Std.Err.	t(11)	p	Coeff.	Std.Err. Coeff.
Mean/Interc.	0.014453	0.001424	10.14702	0.000001	0.014453	0.001424
(1)Voltage (V)	0.006145	0.002849	2.15691	0.053994	0.003072	0.001424
(2)Peak Current (A)	0.004442	0.002849	1.55938	0.147195	0.002221	0.001424
(3)Pulse on Time (µs)	-0.007851	0.002849	-2.75576	0.018697	-0.003925	0.001424
(4)Pulse off Time (µs)	-0.003427	0.002849	-1.20283	0.254293	-0.001713	0.001424

Table 4.10: Significant factor of MRR

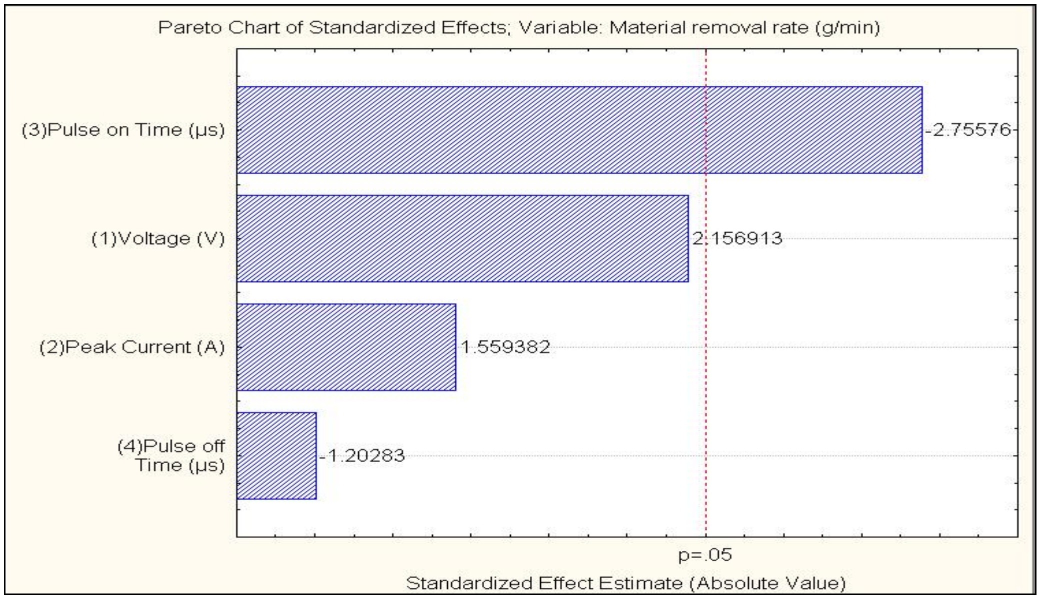

Figure 4.10: Pareto Chart of Standardized Effects; Variable: Material removal rate, MRR.

From the Figure 4.10, view of the result of main effect is determined where the Pulse On Time, µs contributes the maximum effect as main factor. That followed by the voltage, (V) where it still contributes large effect. After that is the parameter of Peak Current, (A) which is gives effect to the MRR. Finally is pulse off time where the contribution of effect is small than the other parameter. This parameter of voltage (V),Peak current (A) and pulse off time can be independent variables because it does not give the significant effect to the MRR.

The significant of main effects are determined where the p value $P<0.05$. The other factors and interaction factors which are not significant are $P>0.05$ and can discarded to produce a reduced model if desired. Their contribution to the variation then goes into error.

4.4.2 Material removal rate, MRR

Again, all the results for MRR have been calculated and shown (refer Table 4.3). According to Figure 4.11 show the higher Pulse On time will be give higher MRR of WC-Co. In addition, the MRR is decreased with the increasing in pulse on time. Figure 4.12 shows that when the voltage are increased the MRR will followed increased. Other than that, the Figure 4.13 shows the result of graph is same with figure 4.12; when the peak current is increased ,MRR will followed increase. For the Figure 4.14,it shows that the increasing the pulse off time,will decrease the MRR but it does not give significant effect to MRR, because the effect is too small.

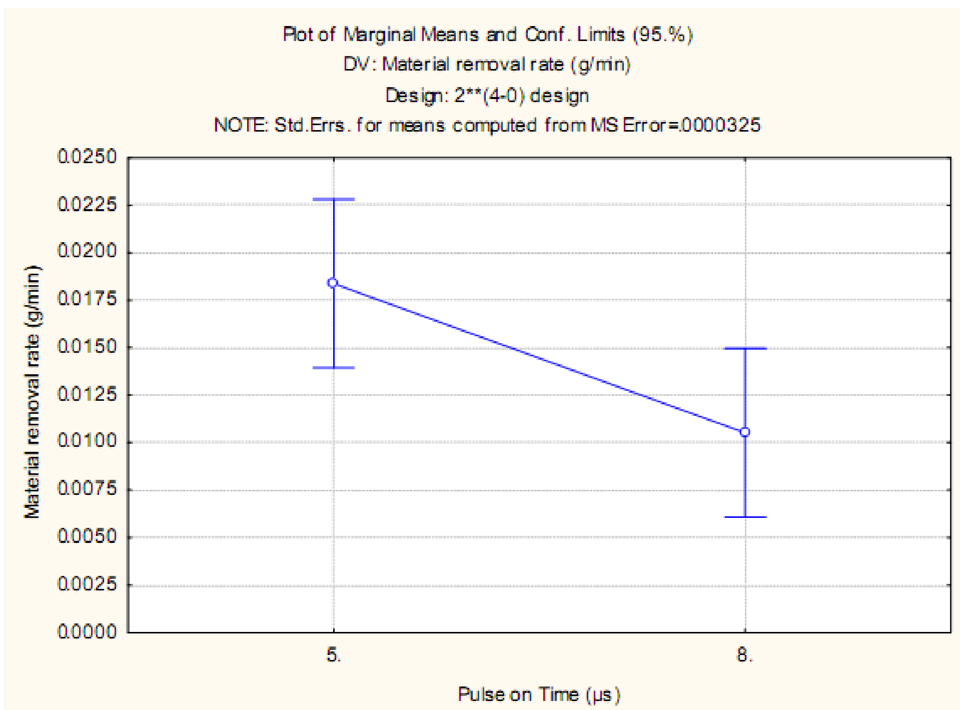

Figure 4.11: Graph of Material removal rate,MRR versus Pulse on Time, (µs)

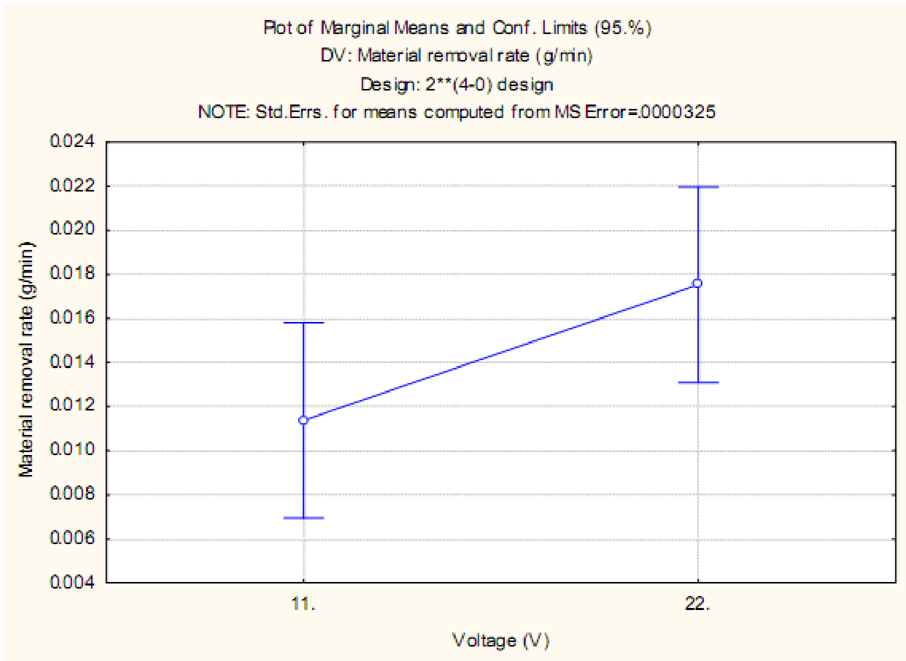

Figure 4.12: Graph of Material removal rate,MRR versus voltage(V)

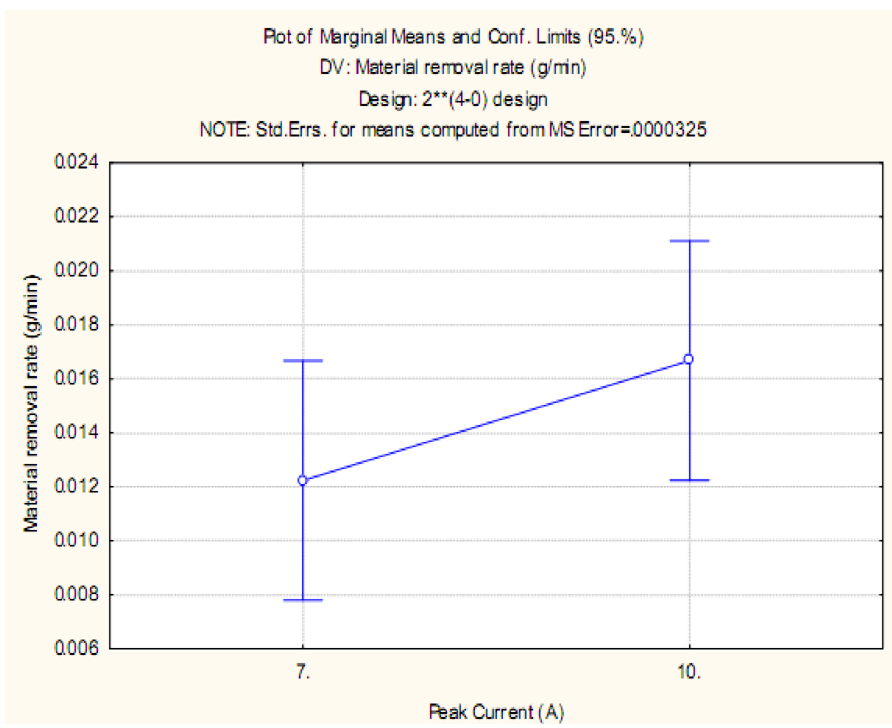

Figure 4.13: Graph of Material removal rate,MRR versus peak current (A)

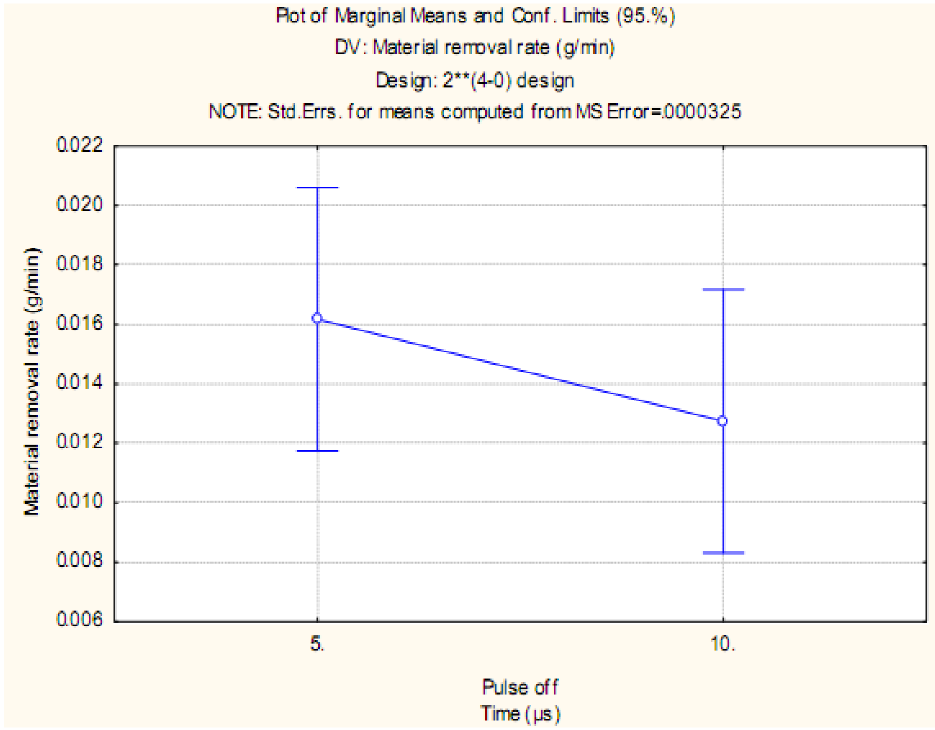

Figure 4.14: Graph of Material removal rate,MRR, versus Pulse off Time, (µs)

4.4.3 Analysis of Variance (ANOVA)

ANOVA applied to the results of experiment to determine the percentage contribution of each factors. This information shows of the factors need to control and which do not.

According to the Table 4.11, there is degree of freedom that contributes error on result. The main factors that need to control or consider is only pulse on time,(C), (red font) where this factors shows high statistical significant, SS and has value of $P<0.05$.

Factor	ANOVA; Var.:Material removal rate (g/min);				
	SS	df	MS	F	p
(1)Voltage (V)	0.000151	1	0.000151	4.652275	0.053994
(2)Peak Current (A)	0.000079	1	0.000079	2.431672	0.147195
(3)Pulse on Time (µs)	0.000247	1	0.000247	7.594218	0.018697
(4)Pulse off Time (µs)	0.000047	1	0.000047	1.446798	0.254293
Error	0.000357	11	0.000032		
Total SS	0.000881	15			

Table 4.11: The ANOVA effect of MRR with no interaction model

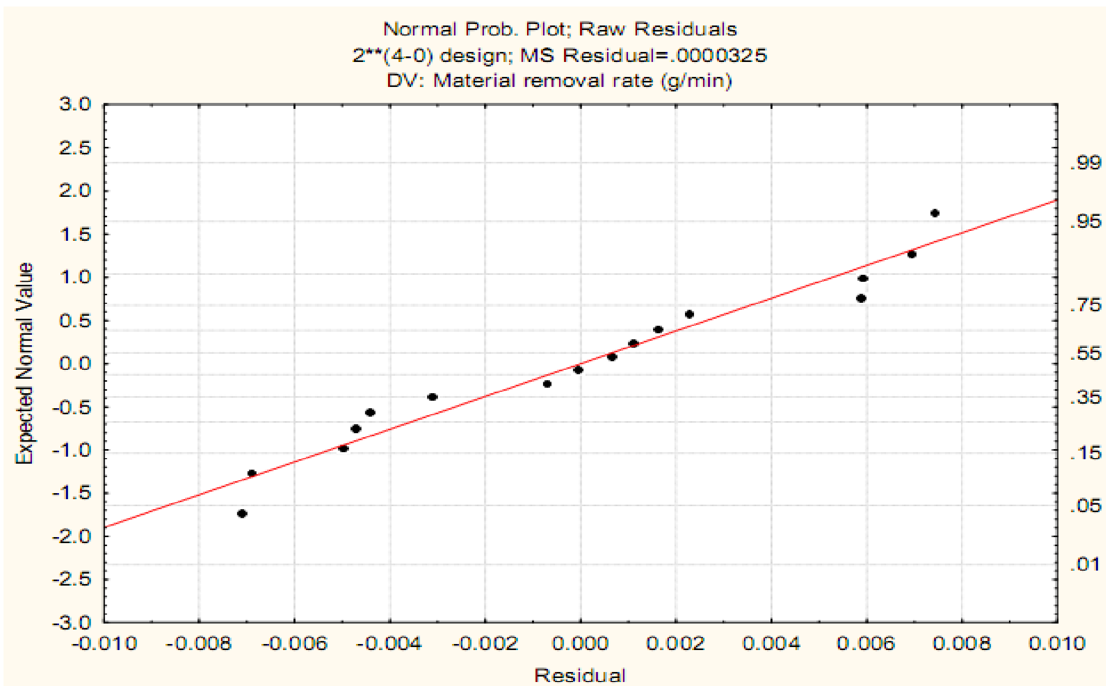

Figure 4.15: Normal Probability Residual plot to Expected Normal Value of effect, MRR

From Figure 4.15 shows the normality of the distribution of a variable, which is extent the distribution of the variable follows the normal distribution. The graph shows the results are proportional between residual and the expected normal values. All effect fall to response and this is an important outcome because all setting gives result to materia removal rate, MRR.

4.4.4 Estimate Result at Optimum Condition

Figure 4.16 will shows a three-dimensional surface plot of data for peak current= 10 A and pulse off time = 5 µs. There is the effect of the interaction between pulse on time and voltage but the higher voltage give the higher value of MRR. So,there is curvature in the response function to the MRR. Invert with the pulse on time because the maximum pulse on time result the low value of MRR. Figure 4.17 shows the same result but in two-dimensional graft. The contour plot show that the red area is more higher value of MRR compare to the green and yellow area. The higher value of pulse on time and low value of voltage contribute low MRR of WC-Co.

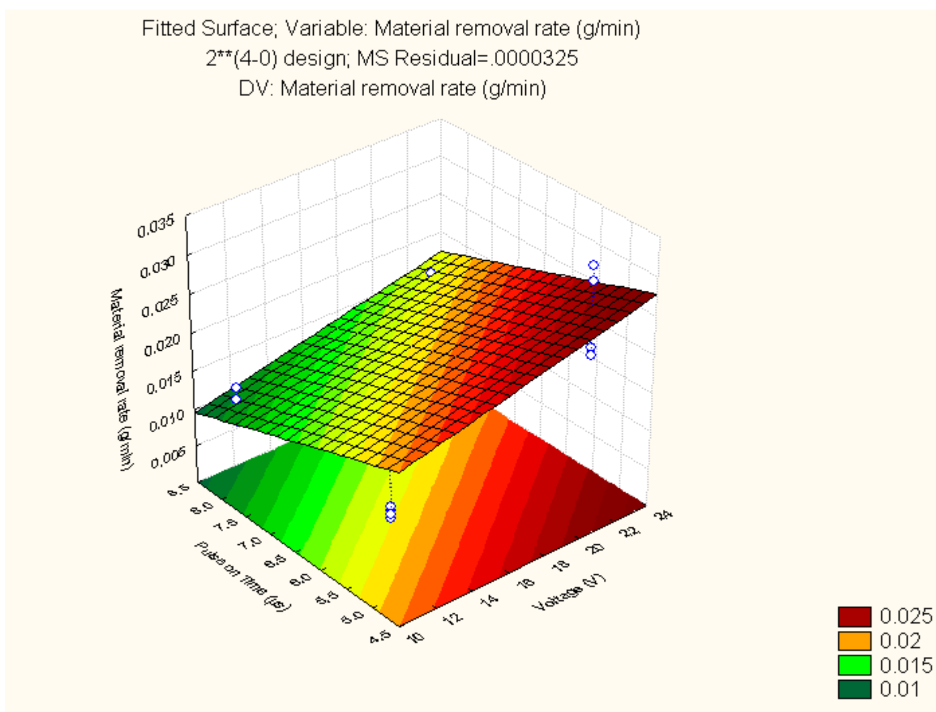

Figure 4.16: 3-D surface plots of the data main effects of the voltage and pulse on time.

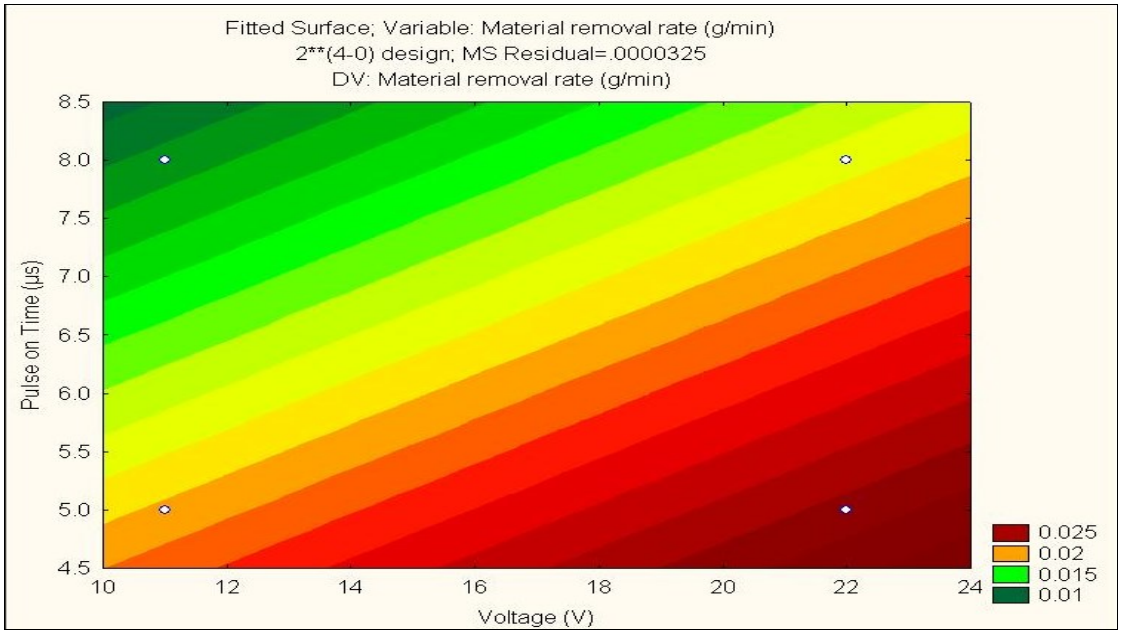

Figure 4.17: 2-D fitted surface distribution of effect between two factors.

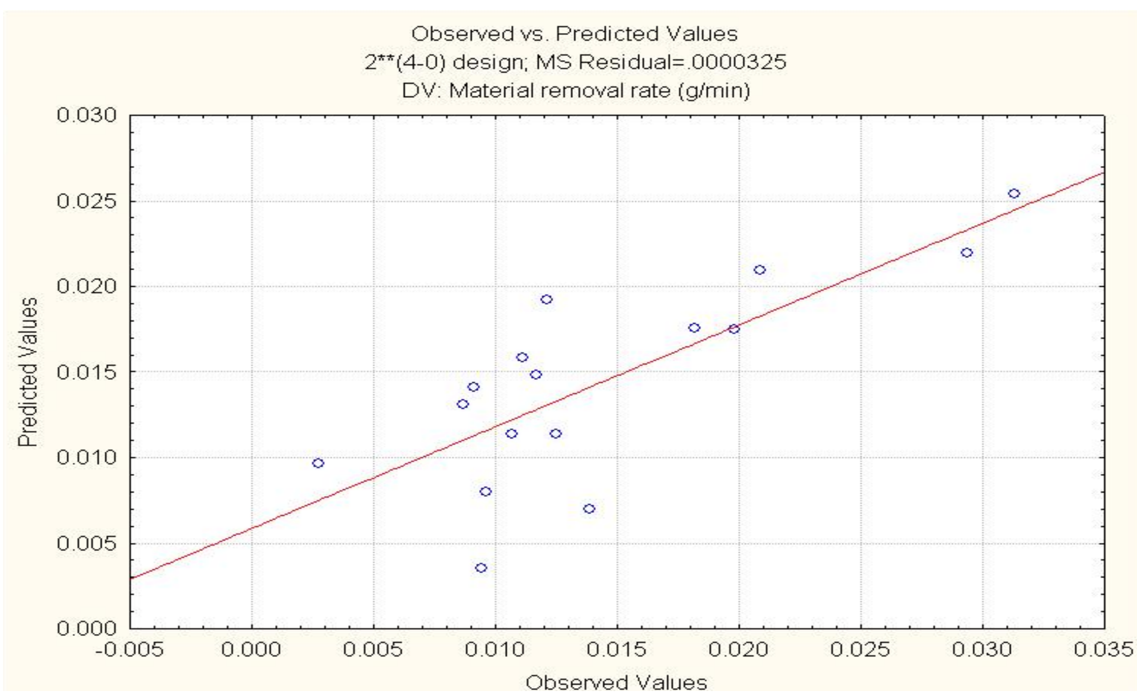

Figure 4.18: Observed Values versus Predicted Values plot of MRR

From Figure 4.18, observed-predicted values are linear and proportional. There is still having error because all the point on the linear line but the distribution is near the line. Overall result can be predicted based on the DOE methodology and STATISTICA software. The desired quality characteristics of MRR can be expressed in Table 4.12.

Table 4.12: Quality Characteristics of Machining Performance of MRR.

Machining Characteristics	Quality Characteristics
Pulse On-time	The low will increase the MRR
Voltage	The high will increase the MRR

The optimum parameter determined:-

i. Pulse On Time= 5 µs
ii. Voltage = 22 V

4.4.5 Confirmation Test

The significant parameters are obtained, and the optimum result also identified, the confirmation test need to be carried out. This is to ensure the theoretically predicted for optimum result will not to vary out of order. The followings are confirmation test result and the predicted value of material removal rate from STATISTICA based on optimum value as shown in Table 4.13 and Table 4.14.

Table 4.13: Confirmation test result of MRR

No of experiment	Material removal rate (MRR) for confirmation test		
	1 Volume of material removed from workpiece (g)	2 Time machining (min)	3 MRR (g/min)
1	0.4377	18.65	0.02347

Factor	Predicted Value; Var.:Material rer 2**(4-0) design; MS Residual=.00 DV: Material removal rate (g/min) Regressn Coeff.	Value	Coeff. * Value
Constant	0.014799		
(1)Voltage (V)	0.000559	22.00000	0.012289
(2)Peak Current (A)	0.001481	10.00000	0.014808
(3)Pulse on Time (µs)	-0.002617	5.00000	-0.013084
(4)Pulse off Time (µs)	-0.000685	5.00000	-0.003427
Predicted			0.025386

Table 4.14: Predicted Value of MRR based on STATISTICA

4.4.6 Comparison Test

The comparison test between theoretically predicted and confirmation test results is a final consideration that will determine weather the optimum parameters predicted are in range. In this investigation, the range or sometimes called margin of error is set bellow than 10%. Margin of error is calculated as follows:

Error Margin (%) =
[{Predicted result- Confirmation test result} / Conformation test result] * 100

Table 4.15: Comparison test result

<table>
<tr><td rowspan="2"></td><td colspan="2">Optimal Machining Parameter</td><td rowspan="2">Error Margin (%)</td></tr>
<tr><td>Prediction (STATISTICA)</td><td>Experiment (confirmation test)</td></tr>
<tr><td>Setting level</td><td>Peak Current= 10 A
Pulse On-time = 5 µs
Pulse OFF-time= 5 µs
Voltage= 22V</td><td>Peak Current= 10 A
Pulse On-time = 5 µs
Pulse OFF-time= 5 µs
Voltage= 22V</td><td rowspan="2">8.14</td></tr>
<tr><td>Material removal rate ,MRR (g/min)</td><td>0.02538</td><td>0.02347</td></tr>
</table>

Table 4.15 show the comparison test between theoretically predicted and confirmation test result for differences set of data on the followings. From the table error margin is 8.14% shows the result is inaccurate. However the result still can be accepted because the error is small. This indicates that DOE Full Factorial method can be used in order to determine optimum parameters.

4.5 ANALYSIS ON ELECTRODE WEAR (EW)

4.5.1 Significant effect

The significant of effect is important in determination of optimum condition. Table 4.16 gives the significant factor from this investigation. The parameters such peak current and pulse off time (red font) as the main effect which contributes more effect of electrode wear, EW in machining process.

	Effect Estimates; Var.:Electrode wear (%); DV: Electrode wear (%)					
Factor	Effect	Std.Err.	t(11)	p	Coeff.	Std.Err. Coeff.
Mean/Interc.	58.7850	1.859036	31.62123	0.000000	58.78500	1.859036
(1)Voltage (V)	5.7925	3.718072	1.55793	0.147537	2.89625	1.859036
(2)Peak Current (A)	17.5525	3.718072	4.72086	0.000629	8.77625	1.859036
(3)Pulse on Time (μs)	1.9350	3.718072	0.52043	0.613077	0.96750	1.859036
(4)Pulse off Time (μs)	-19.4050	3.718072	-5.21910	0.000286	-9.70250	1.859036

Table 4.16: Significant factor of electrode wear, EW

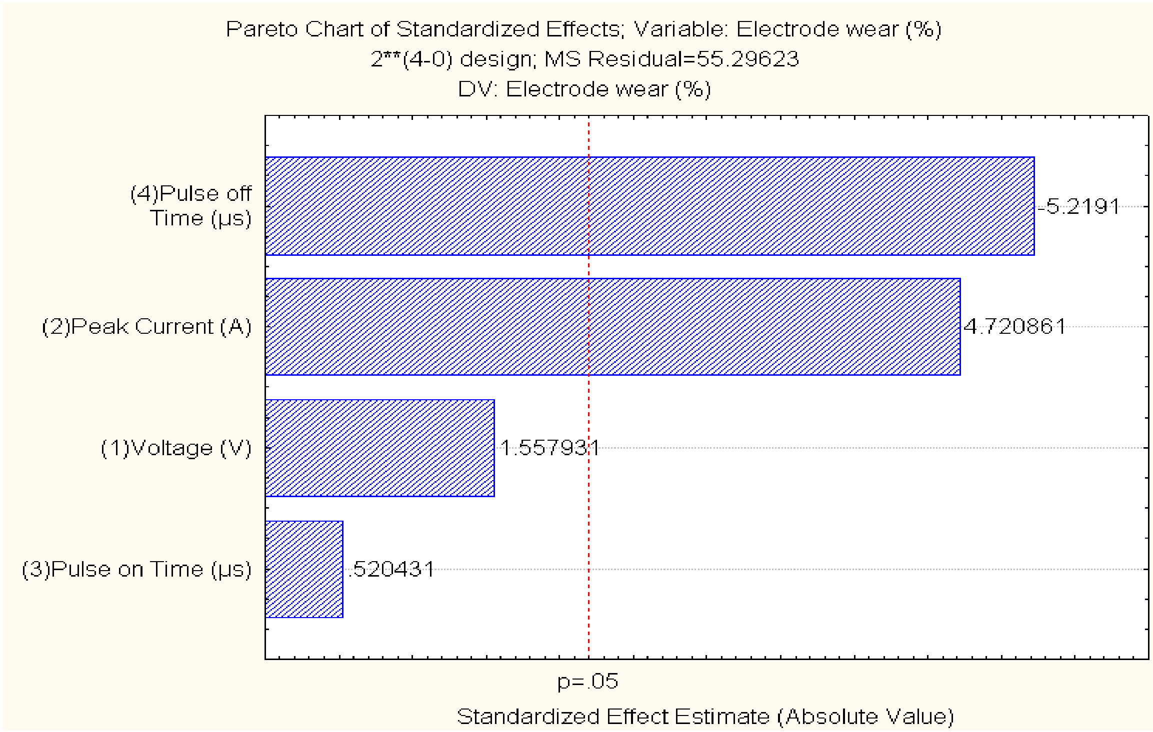

Figure 4.19: Pareto Chart of Standardized Effects; Variable: Electrode Wear,EW.

From the Figure 4.19, view of the result of main effect is determined where the pulse off time, contributes the maximum effect as main factor. That followed by the peak current, where it still contributes large effect. After that is the parameter of voltage which is gives effect to the electrode wear. Finally is pulse on time where the contribution of effect is small than the other parameter. This parameter can be independent variables because it does not give the significant effect to the electrode wear.

The significant of main effects are determined where the p value $P<0.05$. The other factors and interaction factors which are not significant are $P>0.05$ and can discarded to produce a reduced model if desired. Their contribution to the variation then goes into error.

4.5.2 Electrode Wear

Again, all the results for EW have been calculated and shown (see Table 4.3). According to Figure 4.20 show the higher Pulse Off time will be give the low EW of WC-Co. In addition, the EW is decreased with the increasing in pulse off time. Figure 4.21 shows that the result of the graph is different with the result in Figure 4.20; when the peak current are increased the electrode wear will followed increased. Other than that the Figure 4.22, shows the result of graph same with figure 4.23 because when the voltage and pulse on time increased,the EW will also increase. For the figure 4.22 and figure 4.23 shows that these factors does not give significant effect to EW, because the graph is almost flat.

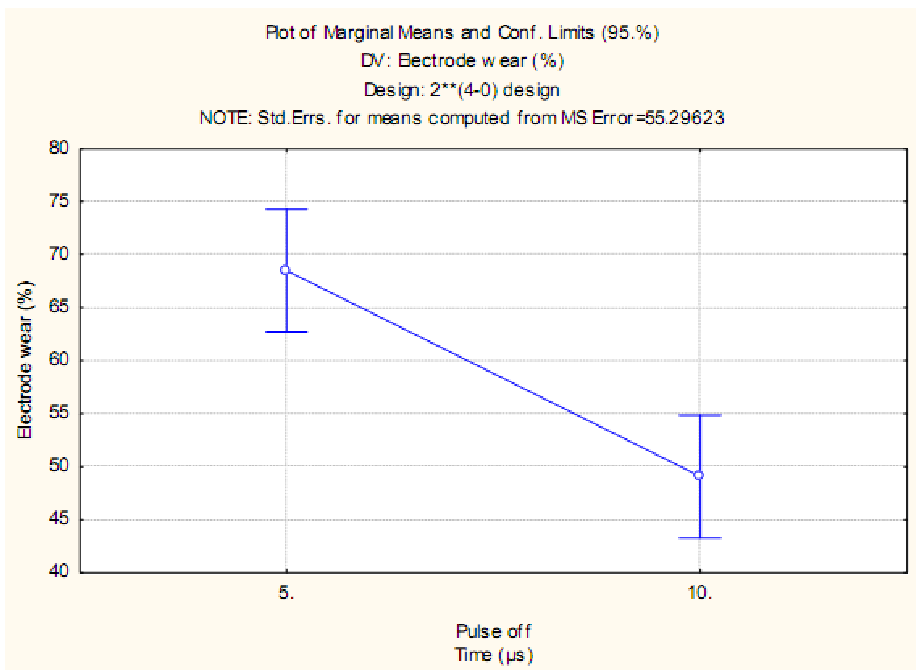

Figure 4.20: Graph of Electrode Wear versus Pulse off Time, (µs)

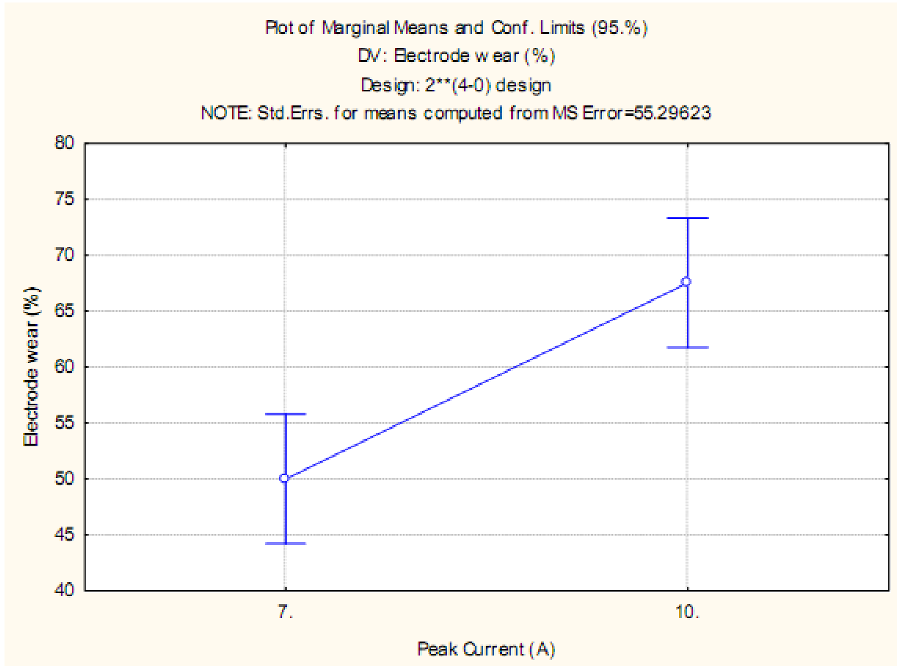

Figure 4.21: Graph of Electrode wear versus Peak current, (A)

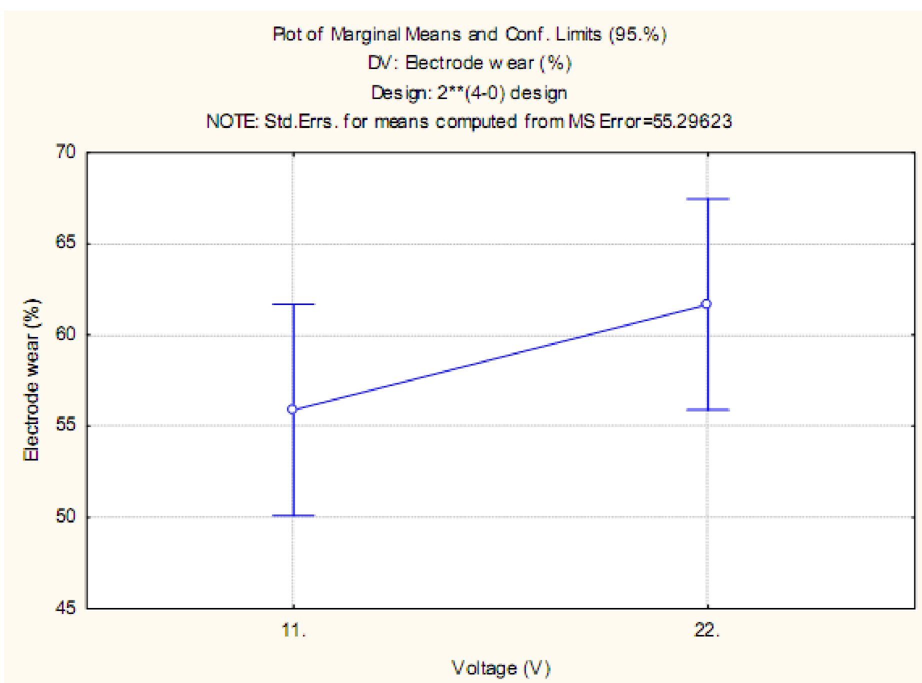

Figure 4.22: Graph of Electrode Wear, EW versus voltage, (V)

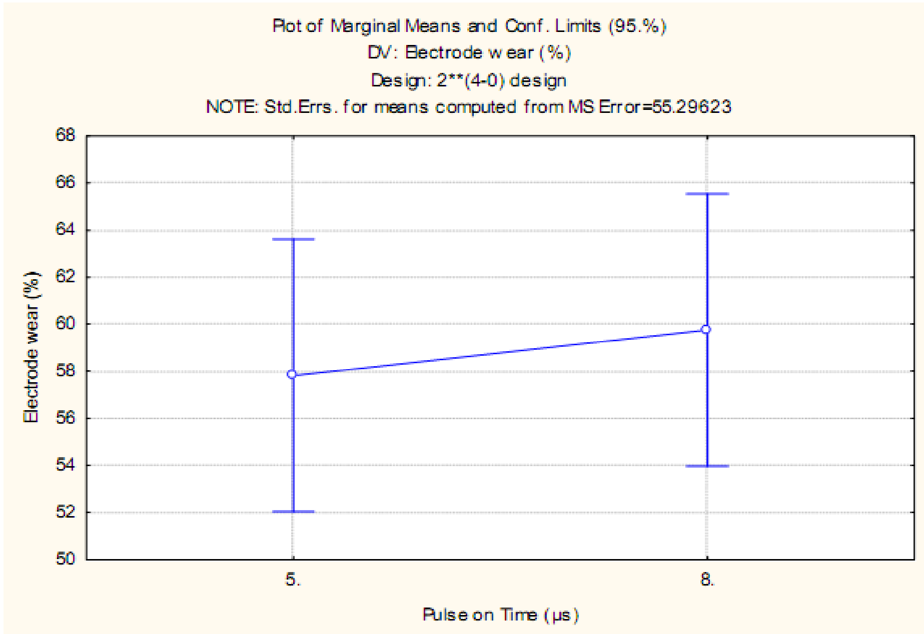

Figure 4.23: Graph of Electrode Wear, EW versus Pulse on Time, (µs)

4.5.3 Analysis of Variance (ANOVA)

Again, ANOVA applied to the results of experiment to determine the percentage contribution of each factors. This information shows of the factors need to control and which do not.

According to the Table 4.17, there is degree of freedom that contributes error on result. The main factors that need to control or consider is pulse off time,(µs) and peak current,(A) (red font) where these factors shows high statistical significant, SS and has value of $P<0.05$.

	ANOVA; Var.:Electrode wear (%); R-sqr=.82601 2**(4-0) design; MS Residual=55.29623 DV: Electrode wear (%)				
Factor	SS	df	MS	F	p
(1)Voltage (V)	134.212	1	134.212	2.42715	0.147537
(2)Peak Current (A)	1232.361	1	1232.361	22.28653	0.000629
(3)Pulse on Time (µs)	14.977	1	14.977	0.27085	0.613077
(4)Pulse off Time (µs)	1506.216	1	1506.216	27.23904	0.000286
Error	608.259	11	55.296		
Total SS	3496.025	15			

Table 4.17: The ANOVA effect of EW with no interaction model

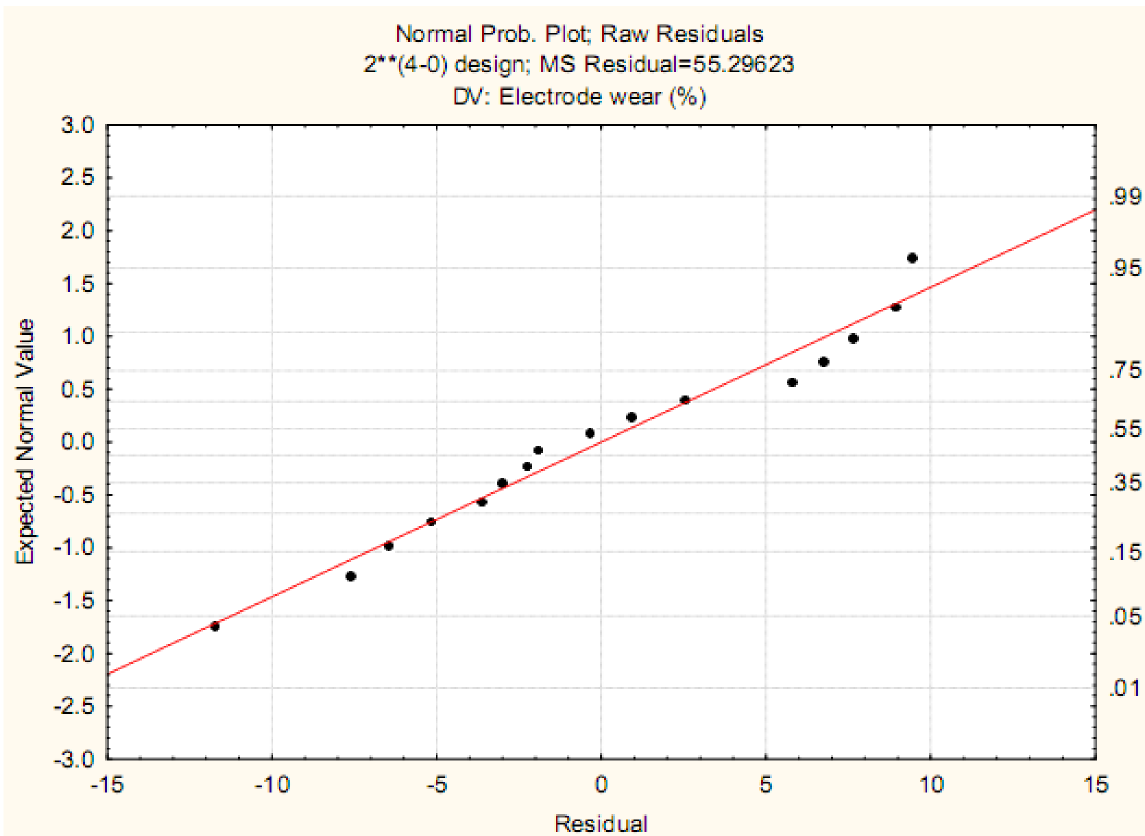

Figure 4.24: Normal Probability Residual plot to Expected Normal Value of effect, EW

From Figure 4.24 shows the normality of the distribution of a variable, which is extent the distribution of the variable follows the normal distribution. The graft shows the results are proportional between residual and the expected normal values. All effect fall to response and this is an important outcome because all setting gives result to electrode wear, EW.

4.5.4 Estimate Result at Optimum Condition

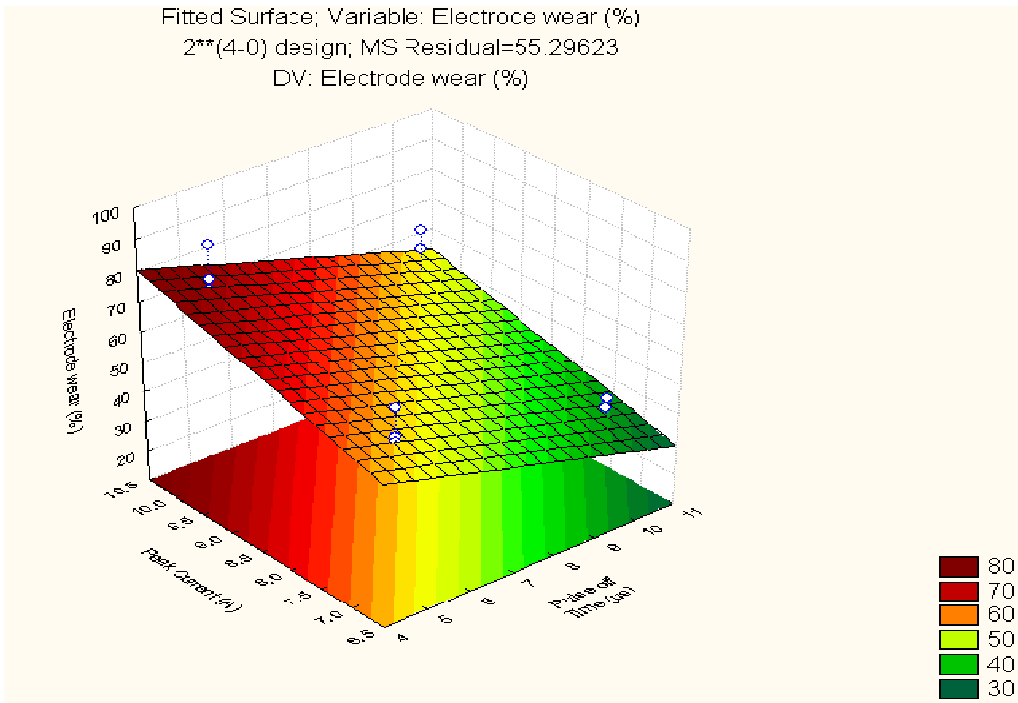

Figure 4.25: 3-D surface plots of the data main effects of the peak current and pulse on time.

From Figure 4.25 present a three-dimensional surface plot of the data for voltage= 11V and pulse on time = 5 µs. Notice that the effect of the interaction between peak current, and pulse off time, (µs) in the data is “twist” plane, so that there is curvature in the response function to the electrode wear. If the data contain no interaction, the surface plot is a plane lying above the peak current and pulse off time. Figure 4.26 shows the two –dimensional with the distribution effect of electrode wear where the data is same. The contour plot show that the red area is more higher value of

EW compare to the green and yellow area The higher value of peak current and pulse on time contribute low electrode wear of WC-Co.

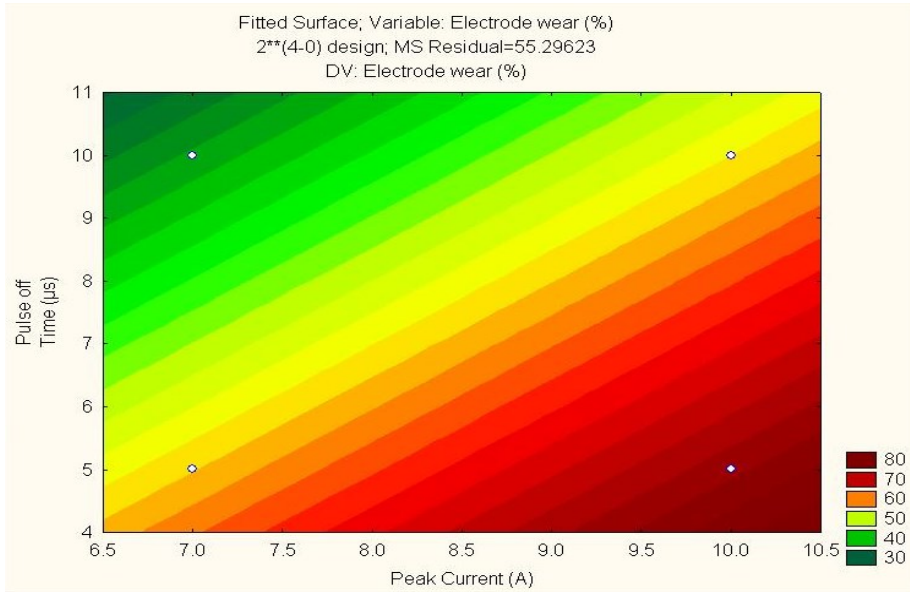

Figure 4.26: 2-D fitted surface distribution of effect between two factors.

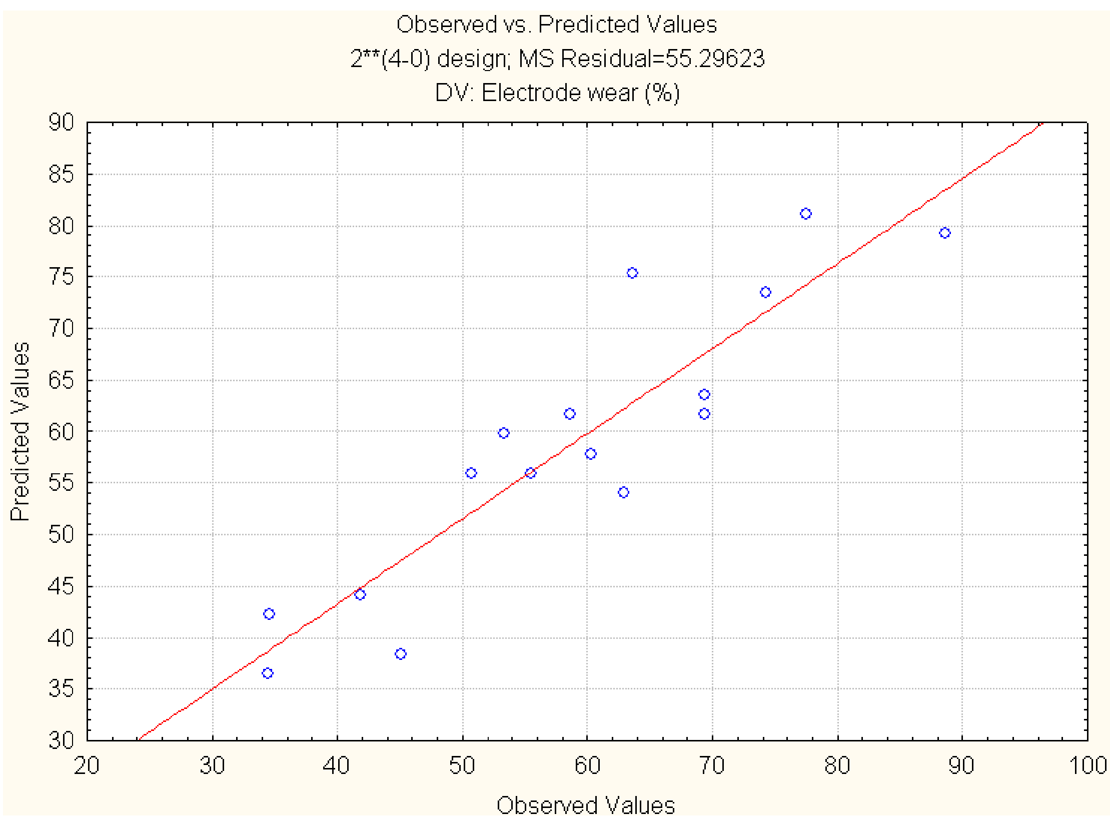

Figure 4.27: Observed Values versus Predicted Values plot of EW

From Figure 4.27, observed-predicted values are linear and proportional. There is still having error because all the point on the linear line but the distribution is near the line. Overall result can be predicted based on the DOE methodology and STATISTICA software. The desired quality characteristics can be expressed in Table 4.18.

Table 4.18: Quality Characteristics of Machining Performance of EW

Machining Characteristics	Quality Characteristics
Pulse Off Time,(μs)	The high obtain the low EW
Peak Current, (IP)	The low obtain the low EW

.

The optimum parameter determined:-

i. Pulse Off Time= 10 μs
ii. Peak current = 7 A

4.5.5 Confirmation Test

The significant parameters are obtained, and the optimum result also identified, the confirmation test need to be carried out. This is to ensure the theoretically predicted for optimum result will not to vary out of order. The followings are confirmation test result and the predicted value of electrode wear from STATISTICA based on optimum value as shown in Table 4.19 and Table 4.20.

No of experiment	Electrode Wear for confirmation test		
	1 volume of material removed from electrode (g)	2 volume of material removed from workpiece (g)	3 electrode wear rate (100%)
1	0.1549	0.4528	34.209

Table 4.19: Confirmation test result of EW

Factor	Predicted Value; Var.:Electrode		
	Regressn Coeff.	Value	Coeff. * Value
Constant	25.27917		
(1)Voltage (V)	0.52659	11.00000	5.7925
(2)Peak Current (A)	5.85083	7.00000	40.9558
(3)Pulse on Time (µs)	0.64500	5.00000	3.2250
(4)Pulse off Time (µs)	-3.88100	10.00000	-38.8100
Predicted			36.4425

Table 4.20: Predicted Value of electrode wear based on STATISTICA

4.5.6 Comparison Test

The comparison test between theoretically predicted and confirmation test results is a final consideration that will determine weather the optimum parameters predicted are in range. In this investigation, the range or sometimes called margin of error is set bellow than 10%. Margin of error is calculated as follows:

Error Margin (%) =
[{Predicted result- Confirmation test result} / Conformation test result] * 100

Table 4.21: Comparison test result of EW

	Optimal Machining Parameter		Error Margin (%)
	Prediction (STATISTICA)	Experiment (confirmation test)	
Setting level	Peak Current= 7 A Pulse On-time = 5 µs Pulse OFF-time= 10 µs Voltage= 11V	Peak Current= 7 A Pulse On-time = 5 µs Pulse OFF-time= 10 µs Voltage= 11V	6.52
Electrode Wear, EW (%)	36.44	34.209	

Table 4.21 show the comparison test between theoretically predicted and confirmation test result for differences set of data on the followings. From the table error margin is 6.52 % shows the result is inaccurate. However the result still can be accepted because the error is small. This indicates that DOE Full Factorial method can be used in order to determine optimum parameters.

4.6 Discussion

Surface roughness (Ra)

i. For the minimum value of Ra, the most significant parameter is pulse OFF-time followed by voltage, peak current and pulse On-time.
ii. The optimal machining parameters are the machining pulse on time at 5 µs, peak current at 7 A, voltage at 11 V and pulse OFF-time at 5 µs.
iii. Parameter that must be control to get the better surface quality is pulse off time and voltage

Material removal rate (MRR)

i. For the maximum value of MRR, the most significant parameter is pulse ON-time followed by voltage, peak current and pulse OFF-time.
ii. The optimal machining parameters are the machining pulse on time at 5 µs, peak current at 10 A, voltage at 22V and pulse OFF-time at 5 µs.
iii. Parameter that must be control to get high MRR is pulse on time.

Electrode Wear (EW)

i. For the minimum value of EW, the most significant parameter is pulse Off-time, followed by peak current , voltage and pulse ON-time.
ii. The optimal machining parameters are the machining pulse on time at 5 µs, peak current at 7 A, voltage at 11V and pulse OFF-time at 10 µs.
iii. Parameter that must be control to get the low EW is pulse off time and peak current.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Basically, this investigation is successful achieved the objective with the acceptable outcome. This experiment evaluates the machining of WC-Co with a Copper Tungsten as electrode. The Full Factorial Design of Experiment (DOE) is very useful in analyzing the optimum condition of parameters, main effect, and the significance of individual parameter to surface roughness, material removal rate and electrode wear of material.

From the result of the experiment, the result can be summarizing into several element. Beside, the error may occur resulting of interference, equipment damage, unsuitable input, out of machining alignment or lack of real plan. Explaining of due cause are interpret as the cause and effect of overall results. The following conclusion is drawn based on the performance of machining characteristic such as Surface Roughness, R_a.

In the case of the R_a parameter, the most influential factors were voltage followed by the pulse off time,while the peak current and pulse on time was not significant at the considered confidence level. In order to obtain a good surface finish in the case of tungsten carbide,low values should be used for peak current,pulse off time and voltage. In the case of material removal rate,it was seen that pulse on time factor was the most influential,followed by voltage,peak current, and pulse off time.

In order to obtain high values of material removal rate for the case of tungsten carbide,within the work interval considered in this study,one should use, high values for peak current and voltage. Finally ,in the case of electrode wear,it was observed that the most influential were pulse off time ,followed by the peak current factor. Therefore, in order to be able to obtain low values of electrode wear,high values of the pulse off time and low values peak current should be used.

5.2 Future work recommendation

Based on the findings of this project the following recommendation for future works can be made. The suggestions are as follows:

a) Varying the workpiece material with different material such as aluminium, brass and other material to investigate the influence of the parameters on the responses variables.

b) To study surface quality as machining characteristic with the other machining parameters such as Surface cracking (SC), Crater Wear (CW), Surface hardness (SH) and etc.

c) Varying the machining parameters with other parameters such as intensity and duty cycle to investigate the effect on responses variables.

d) To do investigation about the machining parameters that gives significant effect to the fine surface roughness,high MRR and low EW but machining at the short of time. This investigation is useful when the investigator applied at the industrial.

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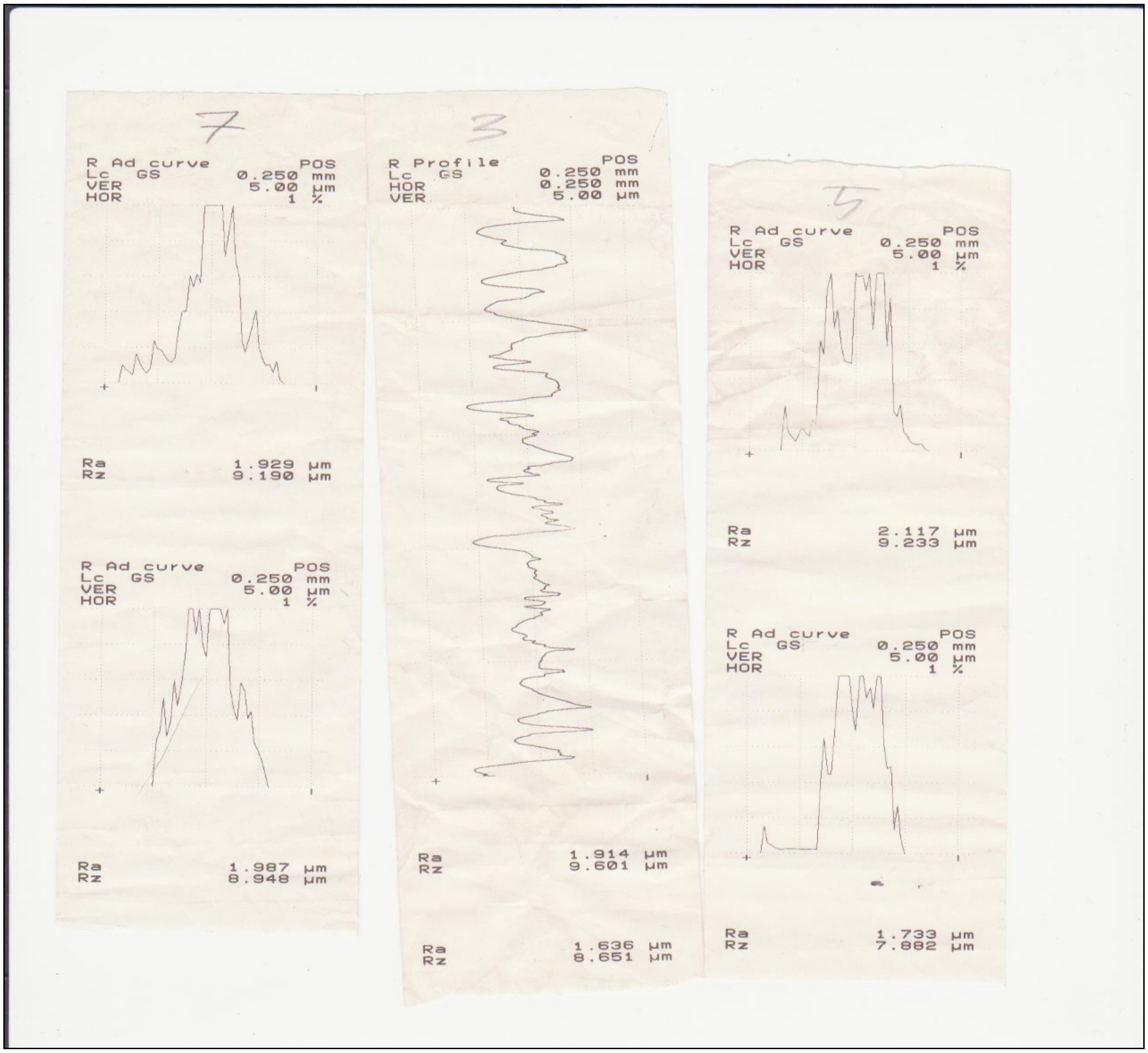
Appendix A.5 Several sample of measuring profile of surface roughness done by Perthometer machine



Appendix A.6 Sample of calculation for calculating various parameters

The calculation base on data collected during EDMing process experiment. The aim of this calculation is to have the values of MRR and EW:

This calculation based on experiment no. 5
From this experiment, the results are:
Machining time (tm) = 25 minutes 56 second ; convert to minutes
= 25.93 minutes

Weight lose of workpiece (WRW) = 0.2899 gram
Weight lose of electrode (EWW) = 0.1824 gram

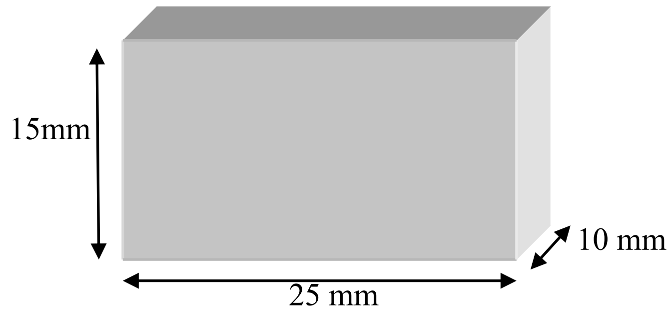
From these results, by using formula 2.1 and 2.2;

$$\text{MRR} = \frac{\text{WRW}}{\text{t}} = \frac{0.2899}{25.93} = 0.0111 \text{ g/min}$$

$$\text{EWR} = \frac{\text{EWW}}{\text{WRW}} x\ \% = \frac{0.1824}{0.2899} x\ \% = 62.92\ \%$$

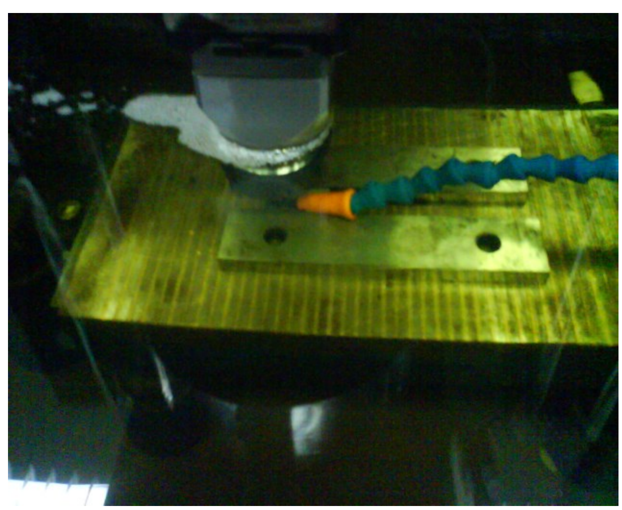
These values were entered to STATISTICA software as responses.

Appendix A.7



Design of one sample of workpiece after cut into 16 pieces

Sample of workpiece after EDMed



EDMed in progress

Appendix A.8 Electrodes for EDM (Mahajan, 1981)

Electrode Material	Form	Wear ratio in finishing	Wear ratio in roughing	Relative cost	Machinability Rating
Graphite	Block,rod, tube,bar	5 : 1	To 100:1	Low	Excellent
Copper	Bar,rod,sheet,wire, tube,forging,stampings	1:1	2:1	Medium	Good
Copper-graphite	Blocks,rods	2:1	4:1	Medium	Fine
Brass	Same as copper	0.7:1	2:1	Low	Good
Zinc alloys	Cast, die casting	0.7:1	2:1	Low	Good
Steel	All forms	1:1	2:1	Low	Excellent
Copper tungsten	Bar,flats,shim stock,rod,wire,tube	3:1	8:1	Medium	Fair
Silver tungsten	Sintered	8:1	12:1	High	Fair
Tungsten	Wire,rod,ribbon	5:1	10:1	High	Poor

Appendix A.9 Specification of Sodick CNC EDM die sink model AQ55L that was used in this experiment

- Ceramic table
- Linear glass scales
- Linear motor for the X, Y, and Z axes
- Automatic fire extinguisher
- Cooling system
- SVC Circuit
- SQ Circuit super quality finish
- LAN interface

Technical Data	
X / Y / Z axis travel (mm)	550 x 400 x 350
Table dimension (mm)	750 x 550
Worktank dims (mm)	950 x 725 x 410
Dielectric level (min - max, mm)	195 - 360
Max. workpiece weight (kg)	1,000
Max. electrode weight (kg)	50
Step resolution (mm)	0.0001
Max. positioning speed (mm/s)	5.0
Max. pulsation speed Z axis (m/min.)	36
Table - chuck distance (mm)	280 - 630
Controlled axes	4
Machine weight (kg)	6,000

C axis	
Resolution (°)	0.001
Rotational speed(min. – max. rpm, continuous)	20 - 2000

Optional features
C axis (4 axes controlled)
C axis SES72 (4 axes controlled)
Electrode changer (4 - 50 positions)
RS232C interface
Uninterruptible power supply (UPS)
LAN facility
STP mode for carbide machining