OPTIMIZATION OF THE ELECTRICAL DISCHARGE MACHINING PERFORMANCE ON TITANIUM ALLOY BY USING STATISTICAL METHOD

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Thesis submitted in fulfilment of the requirements

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EXAMINER DECLARATION

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I certify that the project entitled "Optimization of the Electrical Discharge Machining Performance on Titanium Alloy by using Statistical Method "is written by Maizatul Asnida binti Hassan. I have examined the final copy of this copy of this report and in my opinion, it is fully adequate in term of language standard and report formatting requirement for the award of the degree of Bachelor of Mechanical Engineering

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I hereby declare that the information and record(s) submitted as indicated above is true and correct to the best of my knowledge and belief. Besides that, all parts of this report are the result of my own work**.**

I hereby agree that my candidature may be summarily rejected in case any of the information/record(s) furnished above found to be incorrect or false and I will not make any correspondence in the matter what so ever.

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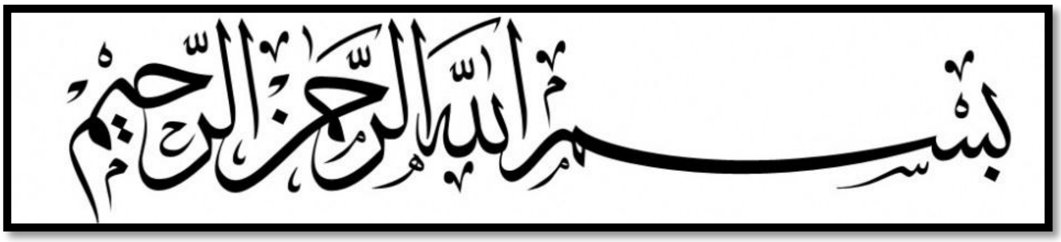

In the name of Allah, The Most Gracious and The Most Merciful

This thesis will dedicated to everybody how always

supported in my project. Thank you

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ABSTRACT

This report will discuss about the aim of this project were to optimize the objective of machining parameters on Titanium alloy workpiece by using the Taguchi method. The machining characteristics such as the material removal rate (MRR), electrode wear rate (EWR), surface roughness (SR) have been recorded in and the analysis of the machining parameters using the copper as a tool or electrode at the cathode and titanium alloy as a workpiece at the anode with the two polarities selected. The method during this project is Design of experiment (DOE) which is an Analysis of Variance (ANOVA) and also the Taguchi method that has been used to define the optimization of single response characteristics. It is called as Taguchi Method that use to formulate the experimental layout, to analysis the effect of each parameter on the machining characteristics and to predict the optimal choice for each EDM parameter. The other, the result from the analysis using Taguchi method will compare with an RSM method to find the best DOE that can be used and from all comparison the most of the best method for the machining performance is RSM method. Thus, higher MRR from the analysis will give the result for the negative and positive copper which is at positive copper higher MRR suggested at peak current (22A), pulse-on time (180μs), pulse-off time (180μs) and servo voltage (95V), lower EWR at peak current (22A), pulse-on time (95μs), pulse-off time (240μs) and servo voltage (85V), and better SR at peak current (22A), pulse-on time (180μs), pulse-off time (240μs) and servo voltage (95V) is the goals and it taken separately in different phase of work during the experiment. The result of the negative copper also has been analysis and the best machining parameter for it also have been selected with the negative copper also come with the best combination of the parameter to optimize the machining performance where for the MRR the best combination of the parameter is at peak current (22A), pulse-on time (180μs), pulse-off time (240μs) and servo voltage (85V), the EWR at peak current (15A), pulse-on time (95μs), pulse-off time (180μs) and servo voltage (105V) is the best level and for the SR, the best combination at peak current (22A), pulse-on time (265μ), pulse-off time (240μs) and servo voltage (95V) is the best level of the parameter of the machining performance. The comparison between Taguchi and RSM method show that the most method that suitable to use is RSM method.

ABSTRAK

Laporan ini akan membincangkan tentang matlamat projek ini adalah untuk mengoptimumkan objektif parameter mesin pada Titanium aloi bahan kerja dengan menggunakan kaedah Taguchi. Ciri-ciri pemesinan seperti kadar penyingkiran bahan (MRR), kadar memakai elektrod (EWR), kekasaran permukaan (SR) telah direkodkan di dalam dan analisis parameter pemesinan menggunakan tembaga sebagai alat atau elektrod pada katod dan aloi titanium sebagai bahan kerja pada anod dengan dua polariti dipilih. Kaedah semasa projek ini adalah reka bentuk eksperimen (DOE) yang merupakan Analisis Varian (ANOVA) dan juga kaedah Taguchi yang telah digunakan untuk menentukan pengoptimuman ciri-ciri tindak balas tunggal. Ia dipanggil sebagai Taguchi Kaedah yang digunakan untuk merangka susun atur eksperimen, analisis kesan setiap parameter kepada ciri-ciri mesin dan untuk meramalkan pilihan optimum bagi setiap parameter EDM. Yang lain, hasil daripada analisis menggunakan kaedah Taguchi akan membandingkan dengan kaedah RSM untuk mencari DOE terbaik yang boleh digunakan dan dari perbandingan yang paling kaedah yang terbaik untuk prestasi mesin adalah kaedah RSM. Oleh itu, MRR lebih tinggi daripada analisis akan memberikan hasil untuk tembaga negatif dan positif yang pada tembaga positif MRR yang lebih tinggi yang disyorkan semasa di puncak (22A), nadi pada masa (180µs), masa nadi-off (180µs) dan servo voltan (95V), EWR lebih rendah pada masa puncak (22A), nadi pada masa (95µs), masa nadi-off (240µs) dan voltan servo (85V), dan SR yang lebih baik pada masa puncak (22A), nadi pada masa (180µs), masa nadi-off (240µs) dan voltan servo (95V) adalah matlamat dan ia diambil secara berasingan dalam fasa kerja yang berbeza dalam eksperimen. Hasil tembaga negatif juga telah analisis dan parameter pemesinan yang terbaik untuk ia juga telah dipilih dengan tembaga negatif juga datang dengan kombinasi yang terbaik parameter untuk mengoptimumkan prestasi pemesinan di mana untuk MRR gabungan terbaik parameter adalah semasa di puncak (22A), nadi pada masa (180µs), masa nadi-off (240µs) dan voltan servo (85V), EWR di puncak semasa (15A), nadi pada masa (95µs), masa nadi-off (180µs) dan voltan servo (105V) adalah tahap terbaik dan bagi SR, kombinasi yang terbaik pada masa puncak (22A), nadi pada masa (265µ), masa nadi-off (240µs) dan voltan servo (95V) adalah tahap terbaik parameter prestasi pemesinan. Perbandingan antara Taguchi dan kaedah RSM menunjukkan bahawa kaedah yang paling sesuai digunakan adalah kaedah RSM.

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μm	micrometre
μs	microsecond
mm^3/min	Millimetre per minutes
%	percentage
A	Ampere
V	volt

LIST OF ABBREVIATIONS

EDM	Electrical Discharge Machining
MRR	Material Removal Rate
EWR	Electrode Wear Rate
SR	Surface Roughness
S/N ratio	Signal of Noise
OA	Orthogonal Array
RSM	Response Surface Methodology
ANOVA	Analysis of Variance
DOE	Design of Experiment

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The classical experimental methods that have design before are too complex and difficult to use. The Taguchi method approach is totally based on statistical design of experiments and this can economically satisfy the needs of problem solving and product/process design optimization (J.A. Ghani et al., 2004). Besides that, it will have more cost and time to complete the experiment if the parameter that been use are many. In the study previously, the Taguchi method is the powerful tool for designing the parameter to get the performance characteristic (N. Tosun et.al., 2004). Therefore the Taguchi methods have been designed for the use of the entire process parameter space but with the small number of experiments. Taguchi method is the other way to design the factorial experiment possesses some advantage such as much quantitative information can be extruded by only a few experiment trail (A. Adnani et al., 2010). The Taguchi method that has been selected for the analysis that will study known as statistical design of the experiment for studying the optimization of the EDM machining performance characteristic with the factor and their level regarding the Orthogonal Array (OA) standard to identify the better input of parameters.

From the design of the Taguchi method, the result will have to estimate using the computer simulation programming on the Minitab software. The software will have the major tools such as the signal to noise and the Orthogonal Array also the ANOVA. The signal to noise is the tool to measure the quality with emphasis on the variation and orthogonal array is accommodating many design factors simultaneously (J.A. Ghani et al., 2004). Moreover, a study of the optimization of the EDM machining characteristic also makes the comparison with the Response Surface Methodology (RSM) where the RSM also one of the methods of design of the experiment. RSM is also known as a collection of statistical and mathematical methods that is useful for the modeling and analyzing engineering problems (N. Aslan., 2007).

Electrical Discharge Machine (EDM) is the one of the machining that used for hard material or for the material that would impossible to machine with traditional technique. This is because, the traditional machining is ineffective. Besides that, the important thing that has remembered about the EDM machining is that it will only work with the materials that are electrically conductive. Electrical Discharge Machine (EDM) is a controlled the metal - removal process that used to remove the metal by producing a rapid series of repetitive electrical discharge between the product and the electrode. EDM process now is the process that has good accuracy and precision with no direct contact between the electrodes or called as the tool with the product therefore it will not have problem involve related to mechanical stress exerted to the product. Since the EDM process does not involve mechanical energy, the removal rate is not affected by hardness, strength or toughness (S.H. Lee and X.P Li, 2001). This method can be used with any other metal or metal alloy such as titanium, hastelloy, kovar , and inconel.

The Electrical Discharge Machine (EDM) has some limitations. The main limitation of the process such as it can only be employed in electrically conductive materials as known before. Besides that, the material removal rate is low and the process overall is slow compared to conventional machining processes. The EDM process usually uses the electrode that made of graphite, brass, copper and copper tungsten alloys (Yan et al., 2000). Therefore, a comprehensive study of the effect parameter such as discharge current, polarity, discharge voltage and others on the machining characteristics is of great significance and could be of necessity.

1.2 PROJECT BACKGROUND

The case studies for this project to find the solution for the problem statement. The maximizing the result for the material removal rate (MRR), minimizing electrode wear ratio (EWR) and smooth surface roughness (SR) should be the outcome at the final. The 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 discharge between the tool that called as electrode and the other part been machined in the presence of the dielectric fluid (C.J. Luis et al., 2005). Traditional machining techniques on Titanium Alloy are often unable to economically machine with precise design required. Hence, electrical discharge machining (EDM) is the most effective machining technique to be used for this purpose.

The electrical discharge machining (EDM) is the machine that has distinct advantages over other machining process and so its use is getting more and more widespread. By using this Taguchi method, the design of experiment to produce the titanium alloy while optimize the machining characteristics will be conduct. In order to have a good machining characteristic, once need to select the proper machining parameters.

Moreover, by the Design of Experiment (DOE) using the Orthogonal Array is use to optimization of the single response characteristic. Consequently, Analysis of Variance (ANOVA) and the F value is also used to determine the significant machining parameter and obtain optimal combination levels of machining parameters. Therefore, some investigate needs to be for getting the best solution of the product by using the electrical discharge machining (EDM). The generally, the expected result that have been found that the higher material removal rate (MRR), the lower electrode wear ratio (EWR), better surface roughness and also no secondary machining.

1.3 PROBLEM STATEMENT

Taguchi methods have been used to design the experiment for finding the optimal parameter that can use and not complex way to use. This is because, EDM machine has poor machining rate or performance due to the material removed rate (MRR) characteristics, that important of the efficiency and cost effectiveness of the EDM process. The less material removed rate (MRR) is occurring in this machining process therefore it will waste and production not good. Second problem involved is an electrode wear ratio (EWR) characteristic. The electrode wear ratio (EWR) is not suitable when it is higher and it will affect the accuracy of product. (EWR) will decreases the accuracy of the product it also maybe because of the (MRR) is not suitable.

When the surface roughness (SR) condition is not in good quality will give other effect to the secondary machining that also influence by the fast material removed rate. Moreover, the (MRR) that need must be higher but the surface roughness (SR) is smooth. Besides that, the secondary machining also effect to this project it will produce product with error such as taper.

1.4 OBJECTIVE

The objective of this project is to

i. Optimize the machining parameters with EDM on Titanium Alloy using Taguchi method
ii. To analyse this project according to higher material removed rate (MRR), lower electrode wear rate (EWR) and lower surface roughness (SR)

iii. To defined the better method for Design of Experiment (DOE) by compare the Taguchi Method and the RSM method

1.5 PROJECT SCOPE

The research scope is limited to the machining parameter that will refer to the electrical parameter on EDM machining such as polarity, peak current, pulse-on time, pulse-off time, servo voltage and others. By using the copper as the tool and titanium alloy as a product the data that have been analyse by using some method. The optimization is the process to present the relationship between parameter using one-way (or one-factor) analysis of variance. The calculation will include for analyse the machining parameter such as maximum MRR, minimum EWR, and smooth SR and prevent secondary machining.

Therefore, the result for the optimization of the machining parameter will be select and it can get the most efficiency result. The quality still need to be maintain or improve, cost will reduce and other advantage and the better method of the design of experiment that can be used for the future.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

There are many type of the test can be approach for the experiment. The most frequently use is the full factorial experiment. However, there are possible combination that must be test but, it will take are very long time and use higher cost to conduct because of the factor use. The Robust design have design the Taguchi method for the important aspect and tool. Therefore, the engineering methodology of the Robust design have to use for obtain the product and process condition. This method have been use because of the high-quality product but the development and manufacturer cost is low the other method (J.A. Ghani et al.,2004) The Taguchi method has be uses to approach for single optimizing characteristic. The Orthogonal array is use to optimization the complicated performance characterises and from the data it will decide the optimal process parameter that selected. Besides that, when experiment in progress the dielectric fluid have constant with the pressure from the flushing and if dielectric fluid is too much also will affect the product that will produce. Improper flushing also can reduce removal rate due to unstable machining condition and arcing around regions with higher concentration (S.H Lee and X.P Li, 2001). Therefore the poor characterises will occur if the factor that influence not be aware.

The Electrical Discharge Machining (EDM) is use because of the process that shaping hard metals, also forming deep and can shaping complex-shape holes by arc erosion in all kinds of electro-conductive materials. Besides, EDM process that involved a transient sparks discharges immersed in a dielectric fluid between the electrode or tool and product (C.J. Luis et al., 2005). It have small gap between it and when the discharge occur it will melt and it remove material from the product shape according the tool shape. The EDM machining uses short duration and high current density when the process remove material between the electrode and the product also EDM not uses any physical cutting force during that process (S.H. Lee and X.P. Li, 2001). The electrodes that have be uses is copper because of this material have high temperature and excellent electrical also thermal conductivity. Thus, the electrode fabricates at high temperature and pressure (H.C Tsai et al., 2003).

The EDM will not affect the hardness and the strength of the material during the cutting process (S.H. Lee and X.P. Li, 2001) but it will low the material removal rate (MRR), higher electrode wear ratio (EWR) and worse surface roughness (SR). Therefore, the (MRR) and (EWR) are the major influence. The performance characteristics for the material removal rate (MRR) should be higher-the-better and for electrode wear ratio (EWR) and surface roughness (SR) are the lower-the-better for the machining.

The titanium alloy have called as “difficult to machine” material because of the poor thermal conductivity and coefficient of the thermal expansion that make the material difficult to cool down the heated and melted work. From this situation, it will affect the material removal rate and the machining surface will be damage (Lin Gu et al., 2012). In this project, EDM will be user to cut titanium for optimizing MRR, EWR and SR

2.2 ELETRICAL DISCHARGE MACHINE (EDM)

Electrical Discharge Machining (EDM) is the one of the non-traditional manufacturing process (C.J. Luis et al., 2005). It the important manufacturing process for the tooling, mould and die industries for several decades. There are two type of EDM machining which is die sinking EDM and wire EDM. The Electrical Discharge Machining (EDM) controlled the metal removal and usually to erode the workpiece, the shape corresponding to that of the tool electrode. From the Figure 2.1, there are about the EDM machine that commonly will discuss and it related between this four different major areas (K.H Ho and S.T Newman, 2003).

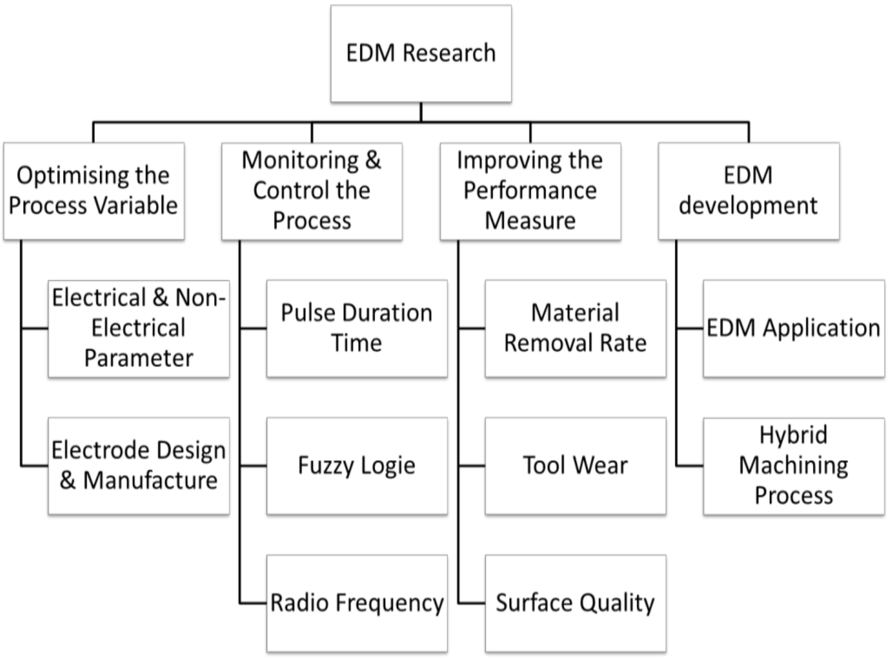


Figure 2.1: Classification of major EDM research areas
Source: K.H Ho and S.T Hewman 2003

Moreover, the EDM common dielectric fluid that usually uses are mineral oil, kerosene, paraffin, distilled water and deionised water which is non-conductor of electricity. The EDM does not make direct contact between the electrode and the workpiece. Besides, it also pumps through the arc gap to flush the material after the cutting. The dielectric fluid involve to clear and low viscosity fluid to make cleaning easier (Norliana Mohd Abbas et al., 2012). The material process at the EDM machine with any hardness can be cut as long as the material can conduct electricity (Norliana Mohd Abbas et al., 2007). Copper is commonly used by the industries, cheaper, and produces good surface finish. Besides that, copper also is a stable material under sparking conditions and gives good surface finish, low diameter overcut, high MRR, and less EWR when machining hardened tool (Norliana Mohd Abbas et al., 2012).

Besides, the electrical discharge machining (EDM) process by using the electrical current which can generates spark erosion between the electrode and the workpiece (P.M. Lonardo et al., 1999). Before do the analysis the process for both electrode and the workpiece will submerged in a dielectric fluid with the fixed small gap or will called as spark gap. The titanium alloy is known as the difficult to cut material but by using the EDM it can be machined effectively. The EDM machine also needs the flushing of dielectric fluid, it will affect the material removal rate (MRR) and the same time influences the surface roughness (SR). The different properties of the dielectric fluid also play a vital role in flushing away debris from the machining gap (K.H. Ho and S.T Newman, 2003). In this project the flushing that will use is kerosene.

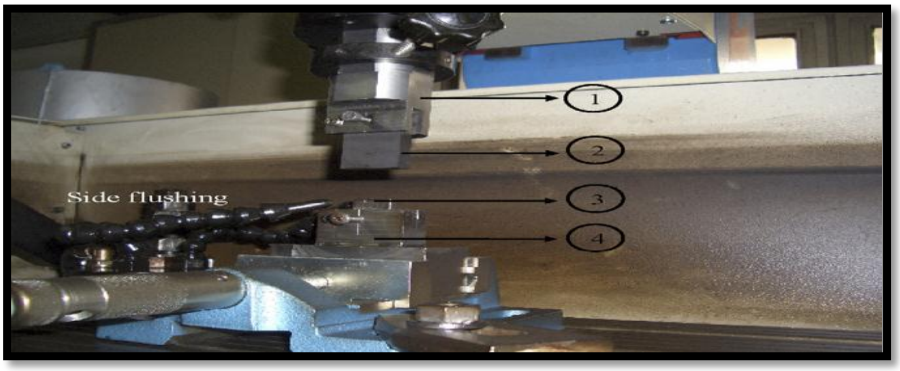


Figure 1.2: Sample of EDM figure. (1) tool holder, (2) electrode, (3) workpiece, (4) workpiece holder
Source: Hascalik and Caydas, 2007

2.3 PROPERTIES OF THE MATERIAL SELECTION

For analysis the optimization of the EDM machining performance, the electrode or tool that been choose is copper. This is because the performed of the cooper is better than graphite electrodes in term of tool wear, surface finish, and tool with positive polarity give higher material removal rate and lower tool wear ratio (S.H. Lee and X.P Li, 2001). The application of the injection flushing is pressure flushing. If it was improper flushing such as wrong selection of the flushing method during the EDM machining, it will insufficient flushing pressure during the machining process it would contribute to erratic cutting, poor machining rate (S.H. Lee and X.P Li, 2001). The proper flushing method is difficult to get the good surface roughness, higher material removal rate and electrode wear ratio also lower secondary machining. During experiment, the flushing brings fresh dielectric fluid (A. Hascalik et al., 2007) which is kerosene into the gap and cools the electrode and workpiece. However, the deeper the cavity and hole will produce the greater the difficulty for proper flushing

Titanium Alloy that using in biomedical application, marine application, and sure in automotive application especially during this experiment that for the valve it consists of two phase of alpha –beta phase of Ti6Al4V alloy (Lin Gu et al., 2012). The EDM process offer a viable and competitive alternative to machine titanium alloy because of the temperature use during the discharge process is much higher than the melting point of all material. Titanium alloy exhibit very excellent technique properties especially in term of strength, hardness and toughness. The analysis of the EDM machining performance have to make because of there will have some problem with the product such as side wall tapering therefore the product produce have not accurate dimension. When the problems occur, it will affect the cost for production, quality of the product, time taken to produce product and more. The properties show in Table 2.1 show below:

Table 2.1: Physical properties of material

Property	**Titanium Alloy**	**Copper**
Density (g/cm³)	4.04 - 4.42	8.904
Melting point (°C)	1649±15	1084.6
Specific heat (J/g.K)	0.56	0.385
Thermal conductivity (W/m.K)	7.2	400
Electrical resistivity (μΩ.cm)	170	1.678
CTE* linear (μm/m.°C)	8.6	16.5

CTE* coefficient of thermal expansion

Source: Lin Gu et al., 2012

In this table show that for this project the Titanium Alloy will be the workpiece and the copper as an electrode or tool.

2.4 DESIGN OF EXPERIMENT (DOE)

The parameter has been performed by many researches but usually it not considers both (DOE) and mathematical formula (ANOVA). Besides that, Design of Experiment (DOE) is using to optimize the machining characteristics by using Orthogonal Array (OA) and then use Analysis of Variance (ANOVA) for analysis. By using Taguchi method, the control factor table is used as reference guide to start and execute experiment. It is the powerful tool for parametric design of performance characteristics to determine optimal machining parameter for get better machining characteristics. There are some factors that (Yaakob, 2008) :

1. Non-electrical Parameter
   - i. Injection flushing pressure
   - ii. Rotational od speed electrode
2. Electrical Parameter
   - i. Peak current
   - ii. Polarity
   - iii. Pulse duration
   - iv. Power supply voltage

Therefore, from all machining parameter there will choosing some of that to control the experiment. In this project the parameter that be use are peak current, pulse-on time, pulse-off time and servo voltage.

Moreover, the Orthogonal Array that required that can be considering between L_9 and L_{18} from the standard Orthogonal Array for this experiment. There will consist of 2-level and 3-level which is representing of the level that preference to the minimum, median and maximum that influence for all machining parameter. For name of this common orthogonal array is the L_9 will present for L_9 (3^4) and L_{18} will present for L_{18} $(2^1 x\ 3^7)$. The array is called orthogonal because the level of the various factors is balance and can be separated from the effect of the other factor within the analyses. However, there will have nine numbers of experiments in the orthogonal array during the project with four machining parameters have been selected where according to the Taguchi method design, L_9 orthogonal array table with the 9 rows that represent the number of experiment. Table 2 shows orthogonal Array standard use:

Table 2.2: Standard Orthogonal Array

Orthogonal array	**No of row**	**Max no of factor**	**Max no of column at these level**			
			2	3	4	5
$\boldsymbol{L_4}$	4	3	3	-	-	-
$\boldsymbol{L_8}$	8	7	7	-	-	-
$\boldsymbol{L_9}$	9	4	-	4	-	-
$\boldsymbol{L_{12}}$	12	11	11	-	-	-
$\boldsymbol{L_{16}}$	16	15	15	-	-	-
$\boldsymbol{L_{16}}$	16	5	-	-	4	-
$\boldsymbol{L_{18}}$	18	8	1	7	-	-
$\boldsymbol{L_{25}}$	25	6	-	-	-	6

Orthogonal Array is the experiment layout for the machining parameter that wills analysis using the Taguchi Method which is Robust Design. The Taguchi Method is the system of cost-driven quality engineering that emphasizes the effective application of engineering strategies rather than advanced statistical techniques (T. Rajmohan et al., 2012). The method provides simple, efficient, and systematic approach to optimize the performance in the experiment. Normally when we do full factorial design, 3^4= 81 experiment if for L_9 have been use will run during that time but it will give effect to the experiment cost prohibitive and unrealistic (T. Rajmohan et al., 2012) same to L_{18} orthogonal array. That why, the Taguchi Method have been choose to use for then parameter design. The orthogonally of is an orthogonal array experiment is not lost by keeping one or more empty column.

When design of experiment, the levels that be used for each factor is the important phase in planning. If use 2-level factor are used, the linear function will fit. When use 3-level factor the quadratic function or curve will fit and same goes to 4-level factor that fit a cubic function. This effect of the number of factor can be seen on the response graph for the MRR, EWR and SR The Taguchi method will measure the performance by record the signal to noise (S/N) ratio from the result where the signal represent the desirable value (mean) and noise represent the undesirable value (standard deviation from mean) for output characteristic (A. Adnani et al.,2010). The S/N ratio are different according to the type of the machining characteristic where for the MRR bigger are better, EWR and SR are smaller are better which defined with different formula.

All of parameter has different influence on the machining performance and the significant parameter will be found using (ANOVA). The relative important of the cutting parameter with respect to MRR, EWR and SR and it investigate using analysis of variance (ANOVA). ANOVA represent the relationship between the parameter with overall process performance. The ANOVA is the simple idea for introduces the no way (or no-factor) analysis of variance and built up to one-way (or one-factor) analysis of variance and eventually to a multi-way (or multi-factor) analysis of variance using the orthogonal array. Moreover, according the graph response for MRR, EWR and SR we can get the F test by using ANOVA equation. Therefore, the significant machining parameter and optimal combination level can be determined.

There are some of the evaluated of performance can be express by using calculation (C.J. Luis et al., 2005) which is:

1)For material removal rate (MRR) can be express as: (2.4.1)

$$\textbf{MRR(g/min)}= \frac{\boldsymbol{WRW}\ (\boldsymbol{workpiece\ removed\ weight})}{\boldsymbol{T}\ (\boldsymbol{period\ of\ machining\ time\ in\ minuter})}$$

2)For electrode Wear Ratio (EWR) express as : (2.4.2)

$$\textbf{EWR (\%)} = \frac{EWW\ (\ elecrode\ wear\ weight)}{WRW\ (\ workpiece\ removed\ weight)}\ \textbf{x 100}$$

3)For surface roughness it calculate by using the surface roughness perthometer

In this analysis, give the attention to the quality characteristic that will included such as higher-the-better (HTB) and lower-the-better (LTB) that needed to see at the machining characteristic such as MRR, EWR and SR. The material removal rate will be the higher the better and for electrode wear ratio and surface roughness need to be lower the better performance response at the final result from the analysis.

Lastly, when do the Design of experiment, based on the experiment result we will do the response graph for Material Removal Rate (MRR), Electrode Wear Ratio (EWR) and Surface Roughness (SR) follow by the each factor. From the graph the choosing level will be select by following the machining characteristics that what higher MRR, lower EWR and lower SR. The data analysis from the Taguchi approach using the Minitab software has been selected to obtain the regression and also graphical analysis. (A. Adnani et al., 2010)

2.5 DESCRIPTION OF PARAMETERS

Sentence descriptions of the parameter that can be optimize:

i. Pulse on duration and pulse interval – amount of time current runs into the gap before turn off. Each cycle has an on-time and off-time, the duration of this pulse and the number of cycles per second (frequency).
ii. Discharge Current – direct current through ionized medium.
iii. Dielectric Liquid Pressure – pressurized dielectric liquid flow through the electrode
iv. Polarity – direction of current flow in relation to the electrode. Have either direct polarity and reverse polarity.

v. Discharge Voltage – make amperes flow in the form of spark. The potential different between electrode and workpiece.
vi. Machining depth – hole depth of cut in EDM machining
vii. Machining diameter – hole diameter of cut in diameter.

2.6 SUMMARY

From the chapter 2, is about the how to get the data, how to analysis, the important data and results that should be get at the end of the project from the previous research and experiment. The chapter 3 will be discussed about the flow of make the project successful by plan the DOE of the project and another to set up the best analysis of the best machining performance at the end of the project

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTODUCTION

This chapter currently discuss about the methodology of this project which is that focus on the sample properties, machine that been use, setup the analyses on the electric discharge machine (EDM) experiment and also procedure for analysis the data using Minitab Software. For the analysis, the data that have been collected have to do some researcher analysis in subsequent chapter using the calculation researcher from other source and analysis. Moreover, methodology involve in investigate problem and solve the design of experiment (DOE) and more. During this Final Year Project (FYP) that divide by 2 semester which is FYP 1 and FYP 2. However, the FYP 1 will cover three chapter about doing the proposal, literature review and methodology planning. In this chapter 3, design the experiment and analysis using Taguchi Method that also included the tool and workpiece, get date collection for analysis and other preparation.

3.2 FLOW CHART

During this project, there have the guideline due to make the project goes smoothly and systematic. Therefore for Final Year Project 1 and 2 show the flow to make this project done on time. In figure below shown:

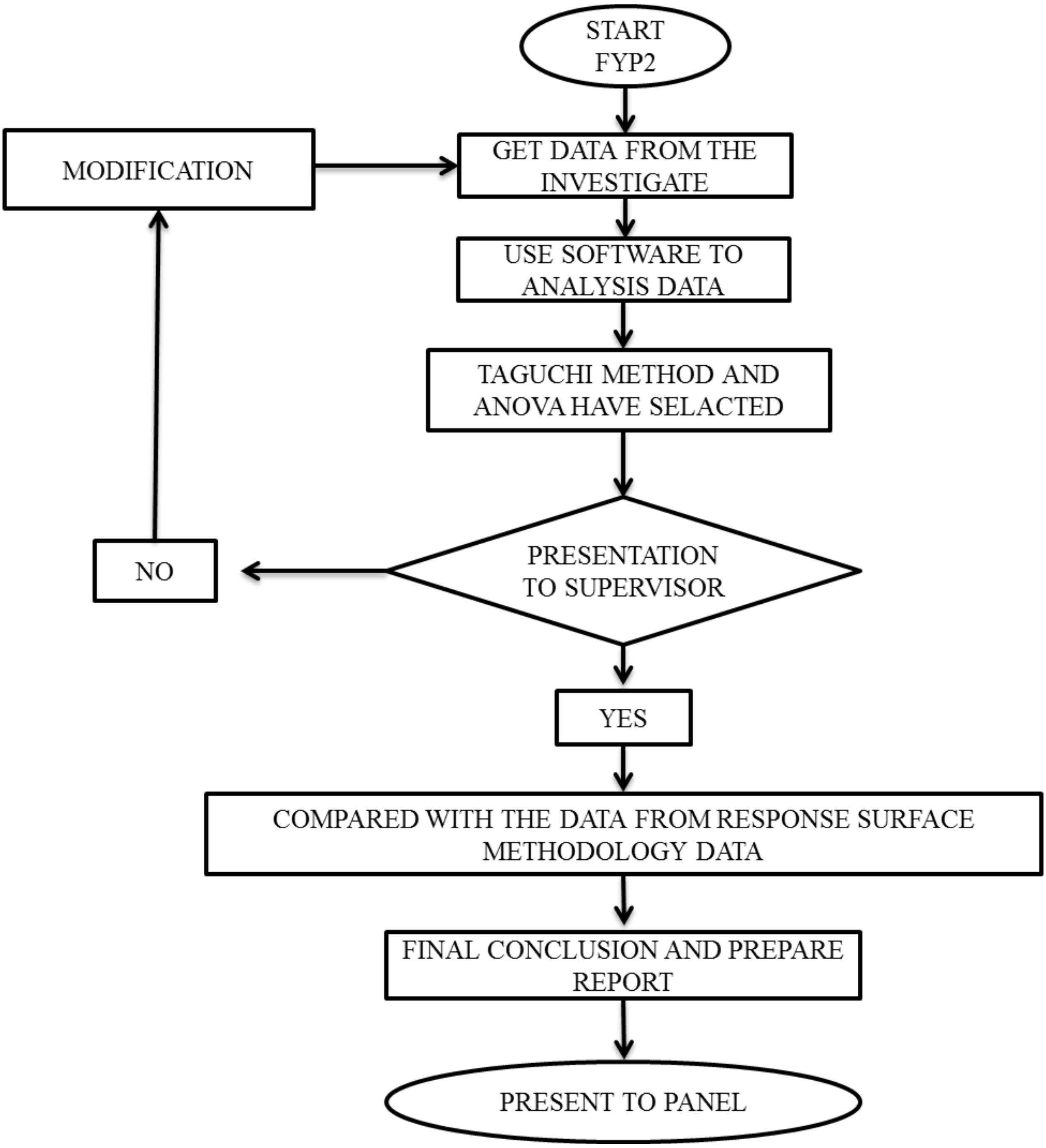


Figure 3.2.1: Flow chart FYP 2

3.3 MINITAB SOFTWARE

Minitab is a statistics package. It was developed at the Pennsylvania State University by researchers Barbara F. Ryan, Thomas A. Ryan, Jr., and Brian L. Joiner in 1972. The Minitab software is known as the statistical analysis software where also have specialized for conducting introductory statistical analysis and graphing. The Minitab software has been choosing because of being accurate, reliable, faster that other method or software such as computing statistics and draw graph by hand.

This software is the powerful software that helps in solves many statistical problems with the easy and smooth way. It also usually use in mathematical, statistic, sports, engineering and other field. However, to do the analysis using Minitab 15 software the equipment that needed to make the analysis successful are:

i. PC with Minitab software
ii. Computer that can save the file
iii. Data to analyses

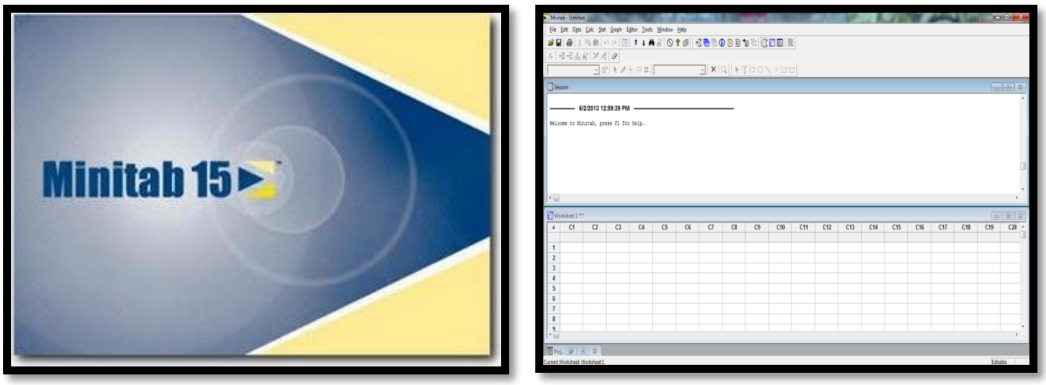


Figure 3.3.1: Minitab software

3.4 DESIGN OF EXPERIMENT

The analysis can be conduct in many methods such as full factorial, Greco-Latin square, Placket-Burman design and Orthogonal Array. The design has been choosing the Orthogonal Array method because it is the most versatile and is becoming more widely used. Orthogonal array consist matrix that arranged in column x rows. The columns represent for specific factor and the rows represent for state of the number of experiment. It will assign a 2-level factor to the 2-level column and six 3-level factors to six of the 3-level column. Since a 2-level factor has one-degree of freedom and 3-level factor has two-degree of freedom, the one 2-level factor and six 3-level control factor required 13 degree of freedom. This orthogonal array is the good choice for this experiment. Table 3.1 will show four EDM parameter used as control factor and their levels that will use from the previous study that will use for investigate for other method:

Table 3.1: The levels of the machining parameters

Process Parameters	Level 1	Level 2	Level 3
	-1	0	1
Peak Current (A)	8	15	22
Pulse-on Time (µs)	95	180	265
Pulse-off Time (µs)	120	180	240
Servo Voltage (V)	85	95	105

The experimental work will been conducted based on the design of experiment from the Taguchi Method. The value for each level also can be called as ±1 and the range value for each parameter has been decided for each level. This design is same for positive polarity and negative polarity. The overall design of the experiment will show in Table 3.2:

Table 3.3: The design of experiment for different parameter as uncoded units

Run order	Peak Current (A)	Pulse-on Time (µs)	Pulse-off Time (µs)	Servo Voltage (V)
1	8	95	120	85
2	8	180	180	95
3	8	265	240	105
4	15	95	180	105
5	15	180	240	85
6	15	265	120	95
7	22	95	240	95
8	22	180	120	105
9	22	265	180	85

There is some information that has to know for the analysis and every set for each experiment it must need the data which is important use in find the optimization of the machining performance. Table 3.3 show the information that use from the previous study:

Table 3.3: Constant Data

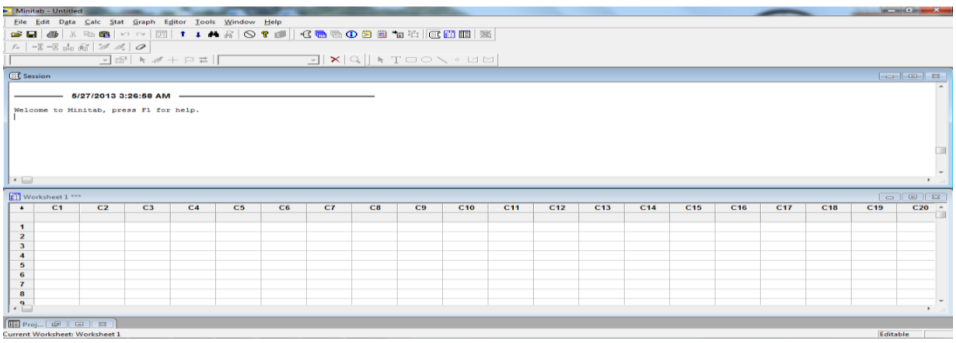
Working Parameters	**Description**
Workpiece material	Ti-6Al-4V
Tool material	Copper
Electrode polarity	Positive and Negative
Voltage	120V
Dielectric fluid	Kerosene
Machining time	40 minutes
Flushing pressure	0.15 MPa

3.5 MINITAB SOFTWARE SETUP

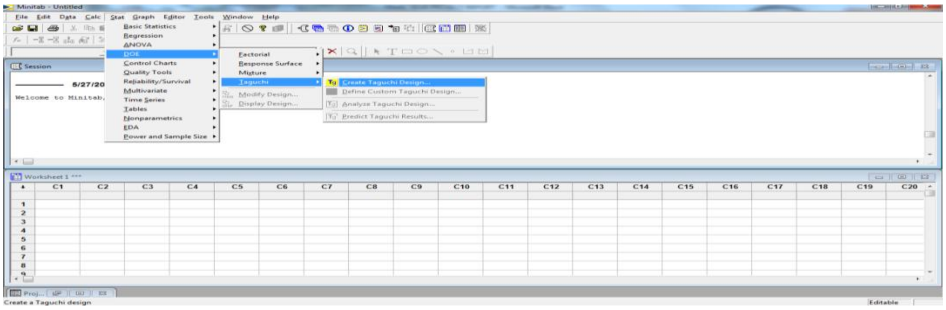
3.5.1 Minitab Software Procedure

After finding all the data such as the parameter and the MRR,EWR and SR value, the S/N ratio and mean are calculated from that the various graph for each parameter that been use will analysis using the Minitab software. To calculate the S/N ratio and mean, the Minitab software used the Taguchi method and for analyses the variance. There are the steps to start the analysis using the Minitab.

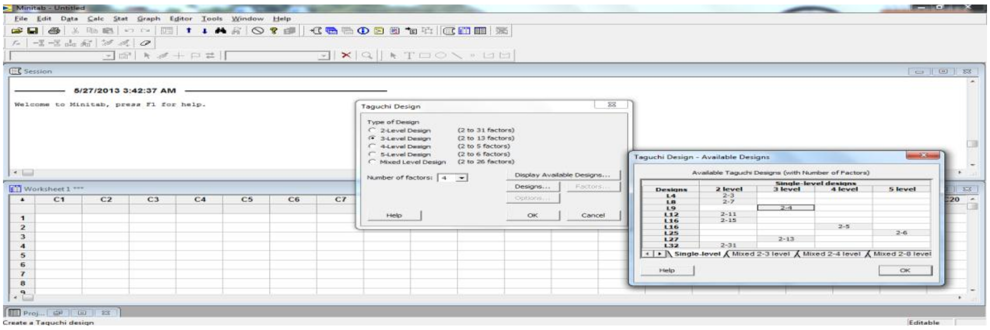
1. Start the Minitab and window will open as show



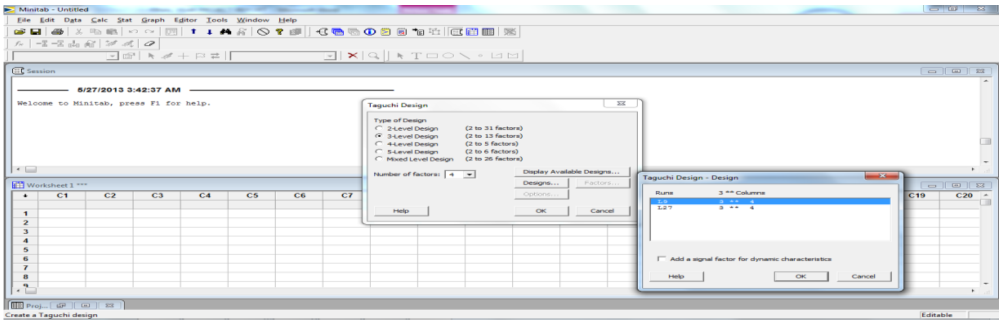
2. To calculate the S/N ratio and mean, the Taguchi Orthogonal Array have to design in the Minitab 15 with the step as show below:



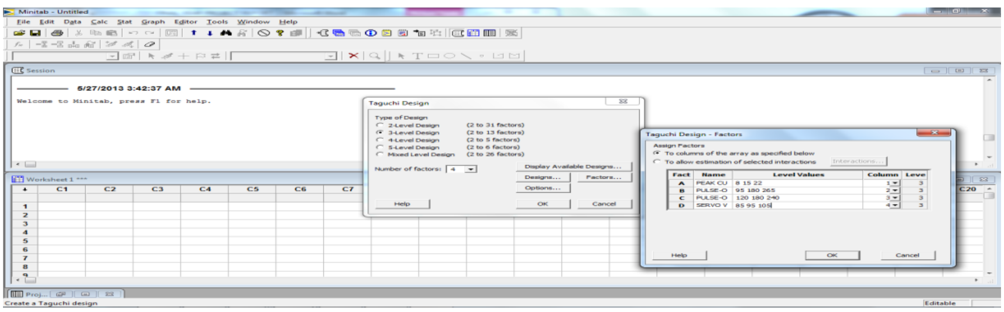
3. Select the type of the design that will use with the number of the factor that have been record before in table 3.2. then click ok



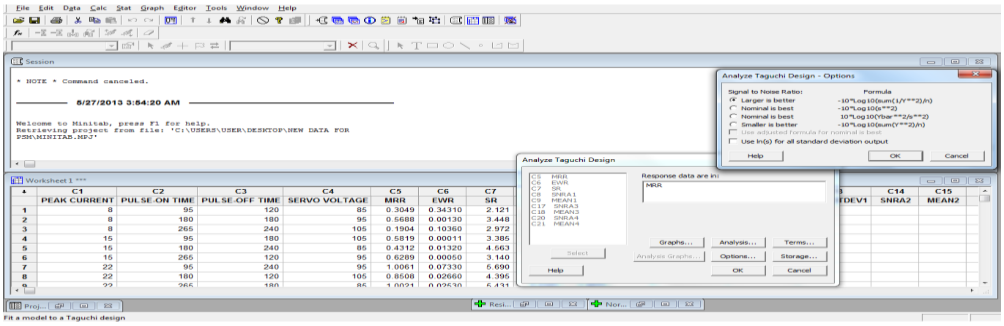
4. Then, click at designs and select L_9 and ok



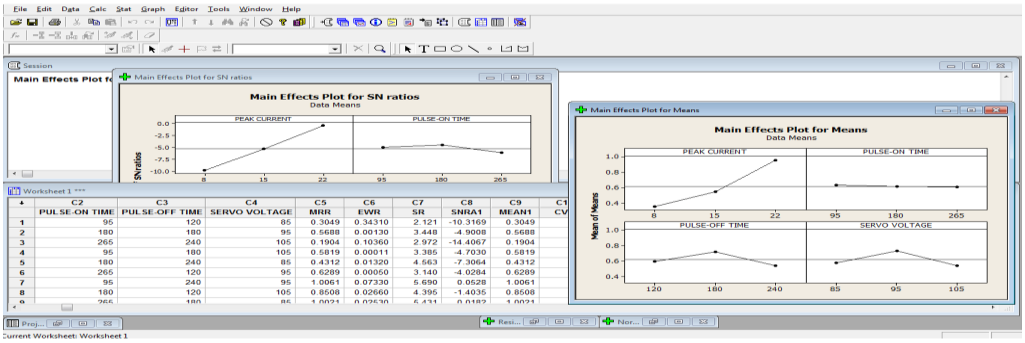
5. Enter the data at the factor. Write the name and level of factor of desired place. Click ok.



6. After complete the table, start analysis Taguchi design – Option. Choose the response data and click the option for choose the quality characteristic.



7. Press OK at Taguchi Design. Graph mean and s/N ratio generate with the data as show.



8. Repeat the procedure for EWR and SR data.

The combination of the workpiece and the tool the respect to the polarity will be use during the experiment where the first result that will analyses by using the Taguchi Method and ANOVA which is using the positive polarity and second set using negative polarity.

3.6 DATA USE FOR ANALYSIS

The data that will be used for the analysis are important part. There are the data that will be used for the analysis using the Minitab15:

i. Machining time, t (constant)
ii. Material Removal Rate (MRR)
iii. Electrode Wear Ratio (EWR)
iv. Surface roughness, (SR)

From the data that have already got from the previous thesis, the expectation result by using the Taguchi Method. It have been provided to make the comparison with the data same using the different method which is used Response Surface Methodology

3.7 ANALYSIS DATA USING ANOVA

This experiment using L_9OA during this study and it will have factor and level of (3^4). In Taguchi Method, most all the observed value is calculated based on higher-the-better and smaller-the-better and also the signal to noise S/N for each of the parameter. The MRR, EWR, and SR have be set as maximum MRR, minimum EWR and smooth SR. Based on ANOVA the optimal combination of the process parameter are predicted. The optimization of the observed value was determined by comparing the standard analysis which is F test and Variance of Analysis (ANOVA) based on Taguchi Method that been use to analysis the experiment. There are so many formula involve during the analysis. Then, it corresponding with analysis of variance (ANOVA) that need to find using formula or by using mini tab software to analysis all the value such as:

i. D.O.F (degree of freedom)
ii. Sum of square
iii. Variance
iv. % contribution
v. F test

To analysis the ANOVA it also using the Minitab 15 software and the one-way ANOVA have been choose for analysis.

3.8 SUMMARY

This chapter carried out the detail about the EDM process experiment that has done under the experiment and the procedure that have be plan in this chapter. The analysis procedure, type of software and others requirement to optimize the machining performance have been done in this chapter. From this experiment the result will be compare with the response surface methodology from other experiment that use same information but with the different design of experiment. These result would further being interpret in chapter 4.

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

In this chapter, the results of the chapter 3 have been analysis using the Taguchi method and also will compare the result from the Taguchi method with the data from the previous research. The number of the experiment and the analysis will be carried out according to the run order in the Minitab 15 software. The Taguchi method for this analysis have the 4 factors with 3 levels each was conducted and the running order will consist 9 runners. The data will analysis using the Minitab 15 Software as mention before to analyses the Taguchi method and the ANOVA. The MRR, EWR and SR of positive copper and negative copper will also find the S/N ratio. The S/N ratio is standing as Signal that represent the desirable value (mean) and Noise for the undesirable value. Both of the terms are for the output characteristics. The use of the S/N ratio is to measure the quality characteristic deviation from the desirable value.

4.2 POSITIVE COPPER

In this study, the random analysis and the randomness of the running order have been carried out according to the run order by the Minitab. The plan of the level of the parameter is shown at chapter 3. The result of the analysis with the respect of machining performance has shown below.

The analysis to help of the Taguchi method using the Minitab 15 Software will represent the response of S/N ratio, response of the mean. The mean response refers to the average value of the performance characteristic for each parameter and also the S/N ratio for each parameter at level 1, 2, and 3 have been calculated.

The main objective for this experiment is to find the find the optimum condition of the EDM machining for material removal rate (MRR), electrode wear ratio (EWR) and surface roughness (SR). The design of the experiment, Taguchi method for this project has been used 2 polarities (positive and negative polarity). Therefore, from the experiment those is conducted by using a copper electrode and titanium as a product the weight before and after experiment for each experiment have been recorded with the constant time machining which is 40 minutes for each experiment. Table 4.1 shows the MRR, EWR and SR by using the formula in Chapter 3.

Table 4.1: Experimental result from EDM of Ti-6Al-4V (positive polarity)

Run exp	**Peak** current **(A)**	**Pulse-on Time (µs)**	**Pulse-off Time (µs)**	**Servo Voltage (V)**	**MRR (mm^3/min)**	**EWR (mm^3/min)**	**SR (µm)**
1	8	95	120	85	0.3049	0.3431	2.121
2	8	180	180	95	0.5688	0.0013	3.448
3	8	265	240	105	0.1904	0.1036	2.972
4	15	95	180	105	0.5819	0.0011	3.385
5	15	180	240	85	0.4312	0.0132	4.563
6	15	265	120	95	0.6289	0.0005	3.140
7	22	95	240	95	1.0061	0.0733	5.690
8	22	180	120	105	0.8508	0.0266	4.395
9	22	265	180	85	1.0021	0.0253	5.431

4.2.1 Analysis of Material Removal Rate (MRR)

The quality characteristics for the material removal rate must be higher value that will represent the better machining performance is called as “Higher is Better” and the graph has been plotting to show it. The results that have produced by analysis by using the selected parameter those give the influence to the machining performance not only to MRR also to EWR and SR performance tabulated in Table 4.2.

The S/N ratio for the MRR equation = -10* Log10 (sum (1/Y**2) /n)…….. (4.1)

Table 4.2: Result of S/N Ratio for MRR

Exp. No	MRR (mm²/min)	S/N Ratio
1	0.3049	-10.3169
2	0.5688	-4.9008
3	0.1904	-14.4067
4	0.5819	-4.7030
5	0.4312	-7.3064
6	0.6289	-4.0284
7	1.0061	0.0528
8	0.8508	-1.4035
9	1.0021	0.0182

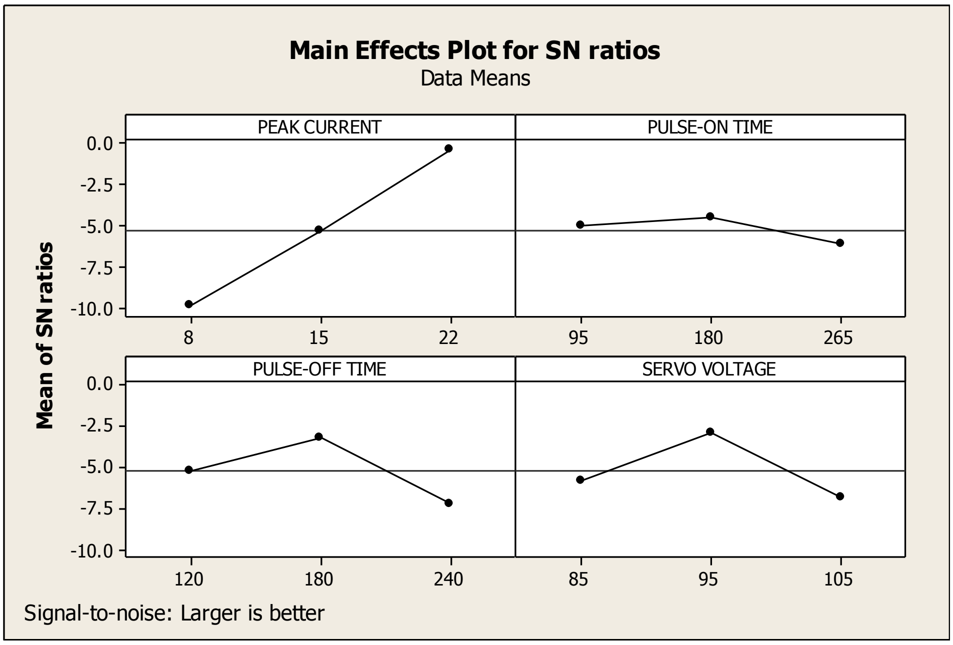
Regarding to the performance characteristics, a greater S/N ratio value will correspond to the better performance. The signal-to-noise is used as the quality characteristics and for MRR the choice characteristics are larger the better characteristic. Therefore, from the Table 4.2 the value of MRR show that at experiment number 7 (22A, 95µs, 240µs, 95V) was achieved the higher MRR (1.0061 mm^3/min) and the lower MRR (0.1904 mm^3/min) was at experiment number 3 (8A, 265µs, 240µs, 105V). Therefore, from the explanation before, that the greater S/N ratio that shows at the experiment 7 corresponding to the better performance of MRR

Table 4.3: Response Table for S/N Ratio in MRR (Larger is Better)

Level	Peak Current	Pulse-on Time	Pulse-off Time	Servo Voltage
1	-9.8748	-4.9890	-5.2506	-5.8684
2	-5.3459	-4.5379	-3.1952	-2.9588
3	-0.4452	-6.1389	-7.2201	-6.8387

Delta	9.4296	1.6010	4.0249	3.8800
Rank	1	4	2	3

Figure 4.1: Response graph for S/N ratio on MRR



The Table 4.3 shows the S/N ratio for each level for peak current, pulse-on time, pulse-off time and servo voltage. The graph it also noticed that the S/N ratio plot calculated for all responses with higher the better criteria according to the S/N ratio equation. . From figure 4.1, the main effect of MRR of each factor for various level conditions.

Moreover, the optimum peak current at level 3 (22mm³/min) and for another 3 parameter increasing with each parameter up to and beyond that it is decreasing with optimum of parameter are level 2 where pulse-on time (180µs), pulse-off time (180µs) and servo voltage (95V). From the detail above, the S/N ratio analysis suggests that by using the maximum level for each parameter, where the peak current at level 3, pulse-on time, pulse-off time and servo at level 2 will present the best MRR.

In order to study the significant of the parameter in affecting the quality performance of the MRR, the ANOVA was performed. By using ANOVA one-way, the result of the machining performance will record when analyses by using the Minitab 15 software. For the results show, the value that needed such as F value, contribution to, mean square and other value. Therefore the tables show the ANOVA analysis for the MRR.

Table 4.4: Table of ANOVA for MRR

Parameter	DOF	Sum of square	Mean square	F	Contribution on (%)
Peak Current	2	0.5594	0.2797	14.93	83.3
Pulse-on Time	2	0.001	0.000	0.00	0.15
Pulse-off Time	2	0.048	0.024	0.23	7.15
Servo Voltage	2	0.063	0.032	0.31	9.38
TOTAL		0.6714			

Therefore, the view of the contribution on the each of the parameters given in Table 4.5, it finds the peak current has dominate the performance characteristic of MRR with 88.3% and the lowest contribution on is pulse-on time with 0.15% only. The F-ratio for the peak current also the higher F-ratio with 14.94 that contribution to be the most significant factor and the lower F-ratio contribution is pulse-on time.

Table 4.5: Regression coefficient for MRR

	Coefficient	SE coefficient	T	P-value	VIF
Constant	0.2632	0.7620	0.35	0.747	
Peak Current (A)	0.04274	0.01043	4.10	0.015	1.000
Pulse-on Time (μs)	-0.0001402	0.0008587	-0.16	0.878	1.000
Pulse-off Time (μs)	-0.000436	0.001216	-0.36	0.738	1.000

Servo Voltage (V)	-0.001918	0.007299	-0.26	0.806	1.000
S= 0.178782		R-Sq = 81.0%			
PRESS= 0.580092		R-Sq(adj)=61.9%			

Based on the regression coefficient table, the result for the first order (linear model) has shown the value of the PRESS (0.580092) and standard error (0.178782). It also observed that the value of R-square (81.0%) and R-square adjusted (61.9%). The closer the value of R-square, the better is the model because show the model can give the reasonable estimation of the parameter. The R - square is used to assure that none of the least square regression is violated. Table 4.5 shows that, there a one parameter with P-value less than 0.05. This means that, the parameter which is peak current is significant at 95% confidence level. Others parameter pulse-on time, pulse-off time and servo voltage are considered less significant toward model term.

4.2.2 Analysis of Electrode Wear Ratio (EWR)

From the result, the quality characteristics for the electrode wear ratio (EWR) also have been an analysis, it means the value for the EWR must be smaller because of the quality characteristics will give better performance to EWR called as “Smaller the Better”. The S/N ratio for the EWR equation is:

S/N ratio =-10* log10 (sum(Y**2)/n……………….(4.2)

The analysis for the EWR has also shown the performance characteristic that must be “Smaller the Better” where representatives from the table 4.6 is the lower EWR is at experiment 6 (0.0005mm³/min) and the S/N ratio given the high value which is 66.0206 that corresponding to the better performance.

Table 4.6: Result for S/N ratio for EWR

Exp. No	EWR (mm³/min)	S/N Ratio

1	0.3431	9.2916
2	0.0013	57.7211
3	0.1036	19.6928
4	0.0011	59.1721
5	0.0132	37.5885
6	0.0005	66.0206
7	0.0733	22.6979
8	0.0266	31.5024
9	0.0253	31.9376

Regarding to the Figure 4.2 and Table 4.6 that relates where from Figure 4.2 the optimal machining performance for the EWR is obtained at peak current at 22A (level 3), pulse-on time at 95µs (level 1), pulse-off time at 240µs (level 3) and for servo voltage at 85V (level1). As MRR, the S/N ratio analysis suggest that, by using the lower level of each parameter which is for peak current and servo voltage (level3) also pulse-on time and pulse-off time (level1) it is the best level for given the minimum EWR.

Figure 4.2: Response graph of S/N ratio in EWR

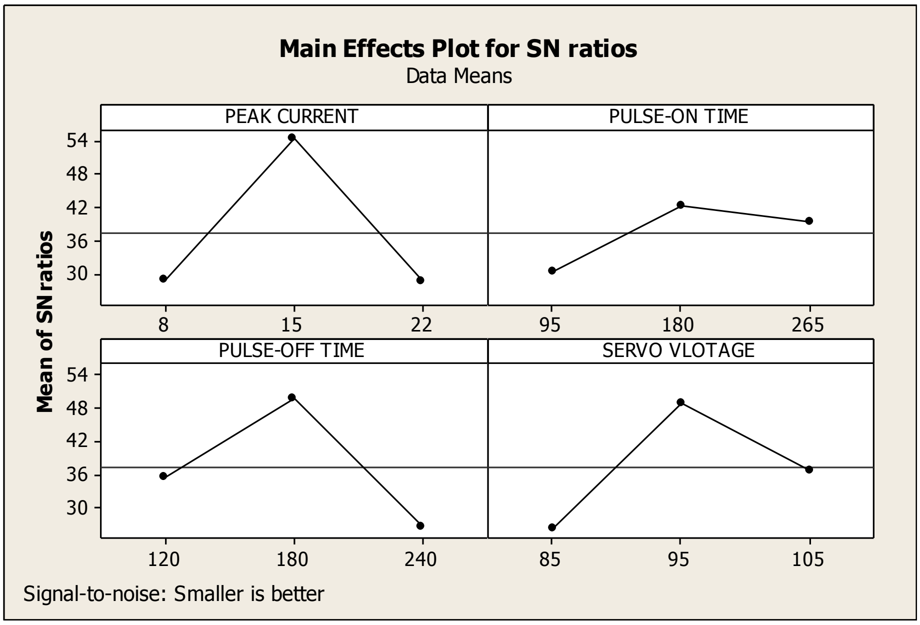


Table 4.7: Response table for S/N ratio in EWR (smaller the better)

Level	Peak Current	Pulse-on Time	Pulse-off Time	Servo Voltage
1	28.90	30.39	35.60	26.27

2	54.26	42.27	49.61	48.81
3	28.71	39.22	26.66	36.79
Delta	25.55	11.88	22.95	22.54
Rank	1	4	2	3

The table above shows the effect of the each parameter that gives the influence of each level. These responses have been shown for the positive polarity that also gives the effect on the machining parameter. From the table, it noticed that the first rank between this 4 parameter is the peak current. It can be prove by analysis the Figure 4.2 with the table above. Besides that, the response table for mean in EWR also shown the same result which is the peak current were noticed in the first rank between all parameter. Figure 4.3 will see the result more clearly and line in the graph shown the mean of the S/N ratio.

Besides that, the EWR also do the analysis by ANOVA one-way. It will give the result for all the parameter that use in this experiment and from that the contribution on between the 4 parameter will be selected which one the best for the EWR.

Table 4.8: Table of ANOVA for EWR

Parameter	DOF	Sum of square	Mean square	F	Contribution on (%)
Peak Current	2	0.0338	0.0169	1.60	34.81
Pulse-on Time	2	0.0258	0.0129	1.09	26.57
Pulse-off Time	2	0.0197	0.0098	0.76	20.29
Servo Voltage	2	0.0178	0.0089	0.67	18.33
TOTAL		0.0971			

The table had shown the tabulated for F ratio of 95% confident level. The higher F-ratio which is 1.60 from Table 4.8 shows that, it is the higher contribution to be the most significant. It is clearly from the ANOVA data from Table 4.8 also, it show the contribution of the peak current is the higher in the record with 34.81% therefore, peak current has the minimum EWR. The contribution for the other parameter is pulse-on time (26.57%), pulse-off time (20.29%) and servo voltage (18.33%).

Table 4.9: Regression coefficient of EWR

	Coefficient	SE coefficient	T	P-value	VIF
Constant	0.7678	0.4760	1.61	0.182	
Peak Current (A)	-0.007686	0.006513	-1.18	0.303	1.000
Pulse-on Time (µs)	-0.0005649	0.0005364	-1.05	0.352	1.000
Pulse-on Time (µs)	-0.0005003	0.0007598	-0.66	0.546	1.000
Servo Voltage (V)	-0.004172	0.004559	-0.92	0.412	1.000
S = 0.111764		R-Sq=48.5%			
PRESS = 0.522987		R-Sq(adj)= 0.0%			

In Table 4.9, the result of the regression coefficient of EWR can see that there are no significant parameters with the P-value less than 0.05. The observation from Table 4.9 also show that, the value of R-square and R-square adjusted also indicates that the model does not generated properly with value R-square is 48.55% and the R-square adjusted is 0.0%. The standard error for the EWR using ANOVA is 0.111674 and PRESS is 0.522987. However, from the result it can determine that the peak current, pulse-on time, pulse-off time and servo voltage are significant in decreasing order.

4.2.3 Analysis of Surface Roughness

The better surface roughness also needs to consider for the quality of the product. With poor surface roughness will give effect to time and cost to produce it. Therefore, the quality characteristics for the surface roughness (SR) also have been analyses for this experiment. The machining performance SR that needed to achieve by represent the better machining performance called as “Smaller the Better”. The S/N ratio for the SR equation is:

S/N ratio = -10* log10 (sum(Y**2)/n)………… (4.3)

Table 4.10: Result for S/N ratio in SR

Exp.No	SR (µm)	S/N Ratio
1	2.121	-6.5308
2	3.448	-10.7513
3	2.972	-9.4610
4	3.385	-10.5912
5	4.563	-13.1850
6	3.140	-9.9386
7	5.690	-15.1022
8	4.395	-12.8592
9	5.431	-14.6976

Moreover, besides the MRR and EWR analysis using the positive copper, the Table 4.10 shows the lowest value of the SR that will corresponding with the greater S/N value for the better performance characteristic. The table show that at experiment 1 the lower SR is determine with 2.121 µm at achieves at (8A, 95µs, 120µs, 85V) with the S/N ratio -6.5308 which is the higher value between all runner.

Figure 4.3: Response graph for S/N ratio in SR

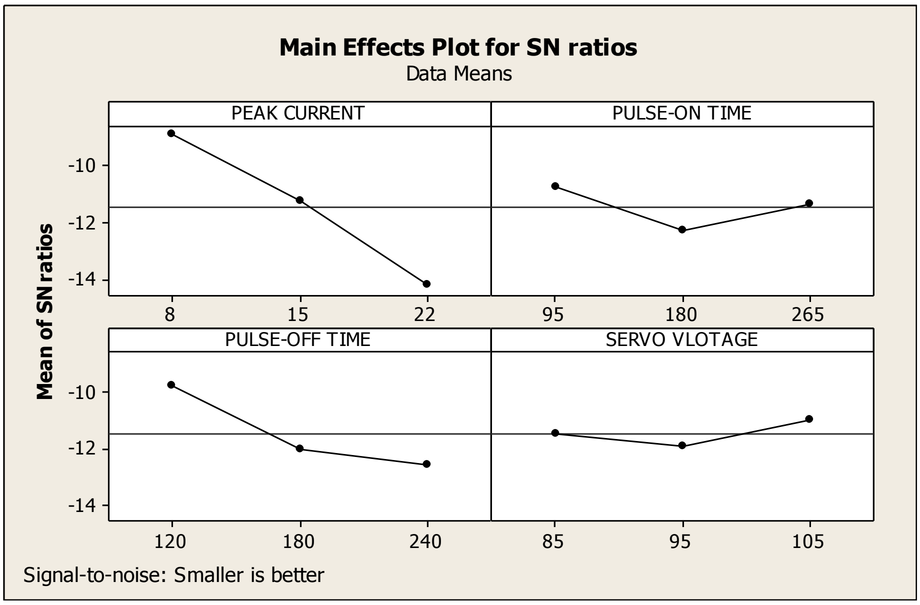


Table 4.11: Response table for S/N ratio in SR (Smaller the Better)

Level	Peak Current	Pulse-on Time	Pulse-off Time	Servo Voltage
1	-8.914	-10.741	-9.776	-11.471
2	-11.238	-12.265	-12.013	-11.931

3	-14.220	-11.366	-12.583	-10.970
Delta	5.305	1.524	2.807	0.960
Rank	1	3	2	4

Table 4.11 shows the main effect for the SR will influence by each level of the 4 parameter that be use during the experiment. The peak current that show above have been selected as the first rank for the SR S/N ratio that be prove the graph that plot in Figure 4.3

The SR machining performance also has to analyses using the ANOVA one-way to find the most suitable parameter use during the experiment. Therefore the optimum machining parameter from the 4 parameter uses especially will be on table below show results of SR. the significant factor from the SR previous graph were calculate using the ANOVA equation in the Minitab software and the result will show in table 4.12.

Table 4.12: Table of ANOVA for SR

Parameter	DOF	Sum of square	Mean square	F	Contribution on (%)
Peak Current	2	8.305	4.153	8.30	73.46
Pulse-on Time	2	0.26	0.13	0.07	2.30
Pulse-off Time	2	2.27	1.14	0.76	20.08
Servo Voltage	2	0.47	0.23	0.13	4.16
TOTAL		11.305			

From the table above, the peak current give the best contribution on with 73.46% and the lowest contribution on is servo voltage with 4.16%. Besides that, the table also show the higher F-ratio (8.30) of contribution to the most significant factor which is peak current that same as show in graph before.

Table 4.13: Regression coefficient of SR

	Coefficient	SE coefficient	T	P-value	VIF
Constant	1.665	1.839	0.91	0.416	
Peak Current (A)	0.16607	0.02516	6.60	0.003	1.000
Pulse-on Time (μs)	0.000680	0.002072	0.33	0.759	1.000
Pulse-off Time (μs)	0.009914	0.002935	3.38	0.028	1.000
Servo Voltage (V)	-0.02272	0.01761	-1.29	0.267	1.000
S=0.431419		R-Sq=93.4%			
PRESS=3.18415		R-Sq(adj)=86.8%			

The regression coefficients for SR are given in table above. The result shows that there are two parameters with P-value less than 0.05. That mean the SR have significant at 95% confident level. The parameters peak current and pulse-off time is the parameter with P-value less than 0.05. On the other hand, the pulse-on time and servo voltage are considered as the less significant toward model term. Besides that, the R-square for the SR is 93.4% and R-square adjusted is 86.8% that indicate that the model is good and valid.

4.2.4 Regression Coefficient

Moreover, the formulae that have use to analyses the data get from the Minitab software will also make the comparison between these methods have been occur. The formula or the equations for each machining performance occur according to the table of each machining performance such as:

MRR = 0.263 + 0.0427 peak current - 0.000140 pulse-on time - 0.00044 pulse-off time - 0.00192 servo voltage

EWR = 0.770 - 0.00769 peak current - 0.000563 pulse-on time - 0.000500 pulse off time - 0.00419 servo voltage

SR = 1.67 + 0.166 peak current + 0.00068 pulse-on time + 0.00991 pulse-off time - 0.0227 servo voltage

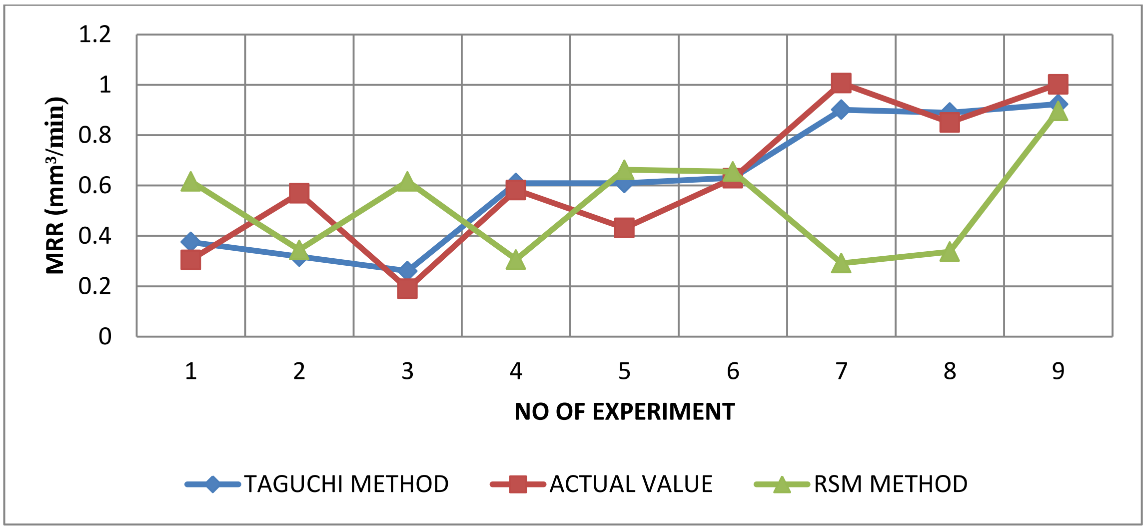
The mathematical modelling that represents the regression table has been given based on the statistical analysis. The positive copper and the negative polarity has been use for the MRR and other machining characteristic such as EWR and SR otherwise, the analysis that for the linear term model only. Therefore, the equation that can get by using the regression coefficient will use for the comparison data. The Taguchi method has been conducted to determine the significant of the parameter that consider toward the response variable. From that, the mathematical model for the MRR, EWR and SR were generated as above.

According to the formula that provided above, the result for comparing the data for 9 number of experiment will substitute in the each formula. Therefore the results show the value by using 2 different methods and the actual value from the experiment. One of the method use is RSM method were actually do 31 number of experiment but the Taguchi method only use 9 data for analysis. Therefore, from the RSM table data that will use only 9 data to compare it with the Taguchi.

Table 4.14: The result from comparing three value of MRR using different method

NO OF EXPERIMENT	TAGUCHI METHOD	ACTUAL VALUE	RSM METHOD
1	0.3753	0.3049	0.6167
2	0.3178	0.5688	0.3442
3	0.2603	0.1904	0.6167
4	0.6094	0.5819	0.3059
5	0.6095	0.4312	0.6623
6	0.6312	0.6289	0.6550
7	0.9011	1.0061	0.2914
8	0.8892	0.8505	0.3370
9	0.9229	1.0021	0.8964

Figure 4.4: The material removal rate result between the actual value, Taguchi method and RSM method.

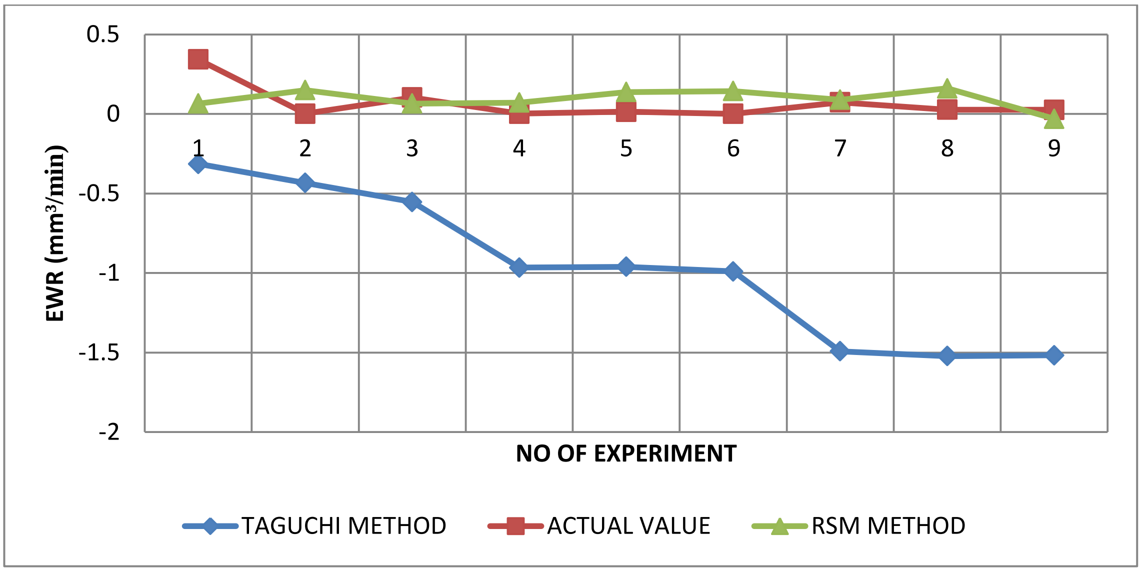


The above table and graph show the comparison between the 3 methods for the MRR, with the data that substitute into the MRR regression coefficient. The best method that is use is the RSM method rather than Taguchi method. The table indicate that the point of each of the experiment show the point of the RSM is the most at the lowest point rather and other. Therefore, by using the RSM method the higher the better performances have been occurring for the machining characteristic.

Table 4.15: The result from comparing three value of EWR using different method

NO OF EXPERIMENT	TAGUCHI METHOD	ACTUAL VALUE	RSM METHOD
1	-0.3143	0.3431	0.06526
2	-0.4341	0.0013	0.14909
3	-0.5538	0.1036	0.06526
4	-0.9660	0.0011	0.07124
5	-0.9607	0.0132	0.1372
6	-0.9904	0.0005	0.14312
7	-1.4926	0.0733	0.08909
8	-1.5224	0.0266	0.16099
9	-1.5170	0.0253	-0.03047

Figure 4.5: The electrode wear ratio between the actual value, Taguchi method and RSM method.

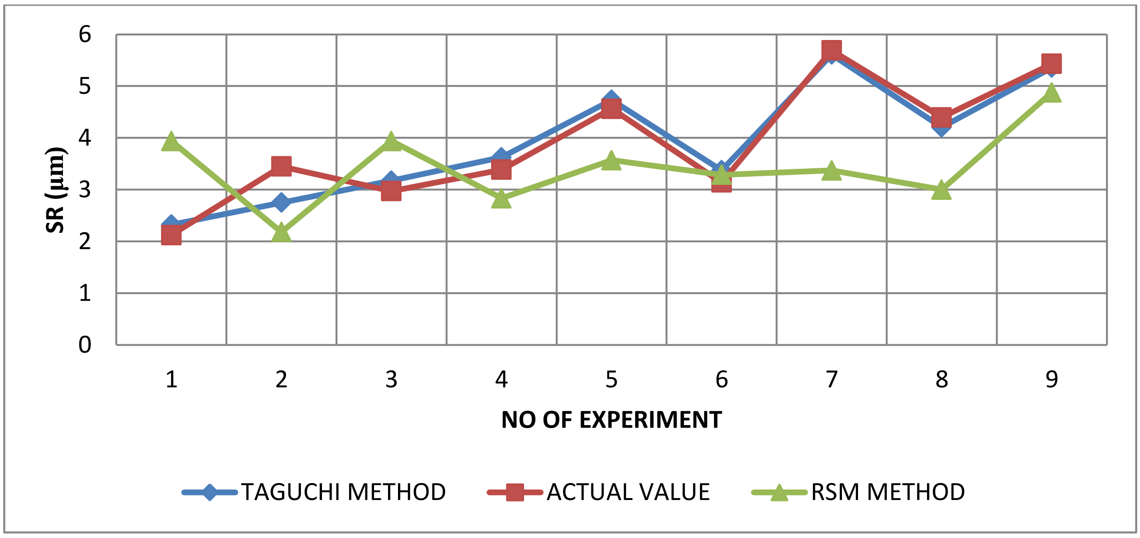


The comparison between the 3 method show that, the best better for the lower EWR machining characteristic shown by using the RSM method. This is because, the RSM value give the lowest value of EWR. Therefore, by using RSM method for experiment and analysis the data the value will give more accurate and relevant rather than Taguchi method.

Table 4.16: The result from comparing three value of SR using different method

NO OF EXPERIMENT	TAGUCHI METHOD	ACTUAL VALUE	RSM METHOD
1	2.322	2.121	3.9382
2	2.748	3.448	2.1816
3	3.173	2.972	3.9382
4	3.625	3.385	2.8340
5	4.731	4.563	3.5676
6	3.373	3.14	3.2858
7	5.609	5.69	3.3708
8	4.205	4.395	3.0002
9	5.356	5.431	4.8762

Figure 4.6: The surface roughness between the actual value, Taguchi method and RSM method.



The RSM is the best method have been shown in figure at the above rather than the Taguchi method where from The table 4.16, the value for the RSM is lower that the Taguchi. Moreover, for the better machining characteristics of SR use the lower quality characteristics .the method that should be use is RSM method that shown the lowest value of SR

From the experiment of the EDM machining, the result has been analyses. The result has been proposed to make are comparison between the actual value from experiment and by using the formulae but with the two different method. From the Table 4.14, 4.15 and 4.1, the comparison has been show using the graph above have been choose the method that will use to get better performance.

4.3 NEGATIVE COPPER

Besides do the positive copper experiment for the EDM, it also conducts the experiment of the EDM by using the negative polarity. The main objective still same with the positive polarity where want to get the optimum condition for the EDM machining of 4 machining performance which is material removal rate, surface roughness and electrode wear ratio. The material use in the Titanium Alloy as is product and copper as are tool. The result show the experiment value for the MRR, SR and EWR after complete the experiment and the needed information has been record. The Table 4.17 shows the result of the MRR, EWR and SR value from using the 4 parameters such as peak current, pulse-on time, pulse-off time and servo voltage

Table 4.17: Experimental result from EDM of Ti-6Al-4V (negative polarity)

Run exp	Peak current (A)	Pulse-on Time (µs)	Pulse-off Time (µs)	Servo Voltage (V)	MRR (mm^3/min)	EWR (mm^3/min)	SR (µm)
1	8	95	120	85	0.1352	0.0227	2.7124
2	8	180	180	95	0.2569	0.0292	3.2576
3	8	265	240	105	0.1048	0.0143	3.4708
4	15	95	180	105	0.2451	0.175	3.4811
5	15	180	240	85	1.0869	0.0316	5.2856
6	15	265	120	95	0.5337	0.0237	5.0843
7	22	95	240	95	0.6548	0.0122	6.3666
8	22	180	120	105	0.6337	0.0307	5.6230
9	22	265	180	85	0.9470	0.0219	6.2592

4.3.1 Analysis of Material Removal Rate (MRR)

Table 4.18: Result analysis of S/N ratio for MRR

Exp.No	MRR (mm^2/min)	S/N Ratio
1	0.1352	-17.3805
2	0.2569	-11.8047
3	0.1048	-19.5928
4	0.2451	-12.2131
5	1.0869	0.7238
6	0.5337	-5.4541
7	0.6548	-3.6778
8	0.6337	-3.9623
9	0.9470	-0.4730

From the Table 4.18, the graph for each parameter has been plotting to find the optimum condition for the MRR during the EDM experiment. The analysis that have been done using the Taguchi method have the result for the S/N ratio for the MRR. The greater value of S/N ratio will correspond to the higher material removal rate (MRR) for the better performance. Therefore, the better MRR have been selected at the experiment 5 (1.0869 mm³/min) with the higher S/N ratio (0.7238). The lower MRR have been noticed at the experiment 2 (0.1048 mm³/min) at also give the lower S/N ratio. The higher MRR give when the data have analyses at the peak current (15A), pulse-on time (180µs), pulse-off time (240µs) and servo voltage (85V).

Figure 4.7: Response graph for S/N ratio in MRR

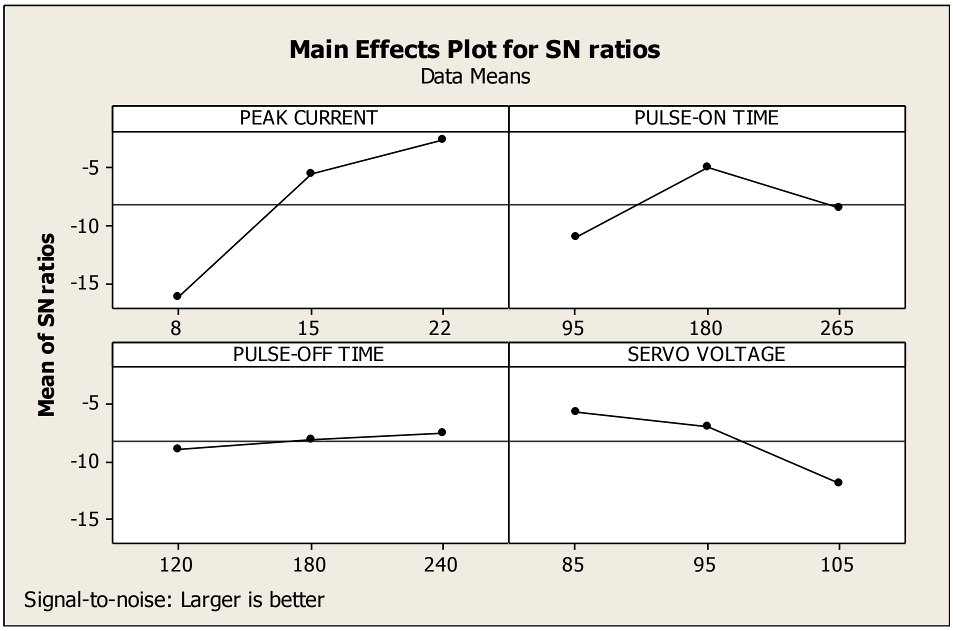


Table 4.7 give the effect of the S/N ratio in MRR with the level that have been selected. Therefore, the S/N ratio suggest that, at peak current (level 3), pulse-on time (level 2), pulse-off time (level 3) and servo voltage (level 1) will been the best level of parameter for the MRR.

Table 4.19: Response Table for S/N Ratio in MRR (Larger the better)

Level	Peak Current	Pulse-on Time	Pulse-off Time	Servo Voltage
1	-16.259	-11.090	-8.932	-5.710

2	-5.648	-5.014	-8.164	-6.979
3	-2.704	-8.507	-7.516	-11.923
Delta	13.555	6.076	1.417	6.213
Rank	1	3	4	2

After the analysis by using the Taguchi method, the data have been analysis by the ANOVA one-way. The result shows that, it similar to the positive polarity at the Table 4.4, 4.7 and 4.10. However, the different is the polarity. Therefore, the value for sum of square, mean square, F-ratio, and the contribution on the experiment for the each parameter show as table below:

Table 4.20: The ANOVA for MRR

Parameter	DOF	Sum of square	Mean square	F	Contribution on (%)
Peak Current	2	0.5592	0.2796	3.81	55.96
Pulse-on Time	2	0.149	0.0750	0.53	14.91
Pulse-off Time	2	0.053	0.026	0.17	5.30
Servo voltage	2	0.238	0.119	0.94	23.82
TOTAL		0.9992			

The ANOVA analysis form each parameter show that the most contribution in the machining parameter is the peak current (55.96%) and the lowest contribution parameter is pulse-off time (5.30%). Therefore, peak current have the maximum effect on the material removal rate (MRR). The higher F-ratio value also at the same choice with the contribution on(%) which is prefer to peak current (3.81) and the second higher on servo voltage (0.94).

Table 4.21: Regression coefficient of MRR

	Coefficient	SE coefficient	T	P-value	VIF
Constant	1.3008	0.8569	1.52	0.204	
Peak Current	0.04140	0.01173	3.53	0.024	1.000
Pulse-on Time	0.0010792	0.0009656	1.12	0.326	1.000
Pulse-off Time	0.001511	0.001368	1.10	0.331	1.000

Servo Voltage	-0.019758	0.008208	-2.41	0.074	1.000
S= 0.201048		R-Sq= 83.8%			
PRESS= 1.05933		R-Sq(adj)= 67.6%			

Based on regression coefficient table, there are also contain the R-square and R-adjusted. The R-adjusted is the variation of the ordinary R-square that affects the number of modal terms. For the complex experiment the model term desirable to be increased or decreased. The regression coefficient for the MRR shows that the value of the R-square is 83.8% and the R-adjusted is 67.6%. The standard error of the MRR is 0.201048 and PRESS is 1.05933. The peak current and the servo voltage show that it has the p-value less than 0.05, therefore it is significant for the machining performance. For the pulse-on time and pulse-off time that has p-value more than 0.05 and it insignificant in model term.

4.3.2 Analysis of Electrode Wear Ratio (EWR)

The analysis as mention before has done for the MRR, EWR and SR. The result for the EWR with the negative polarity has been recorded. The formula that have been use for the analysis is same with the positive polarity experiment in Table 4.22.

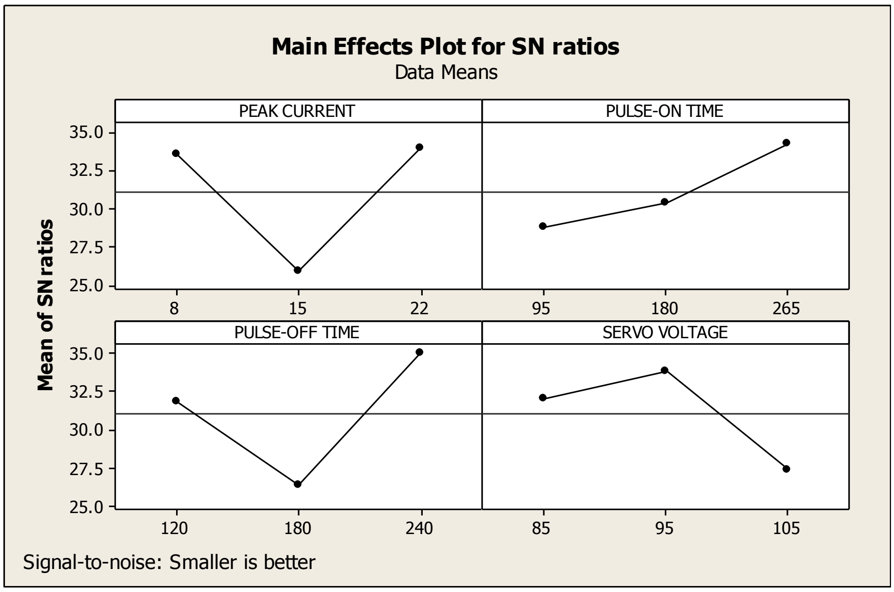
Table 4.22: Experiment result of S/N ratio in EWR

Exp.No	EWR (mm^2/min)	S/N Ratio
1	0.0227	32.8795
2	0.0292	30.6923
3	0.0143	36.8933
4	0.1750	15.1392
5	0.0316	30.0063
6	0.0237	32.5050
7	0.0122	38.2728
8	0.0307	30.2572
9	0.0217	33.2708

The result of the S/N ratio for the EWR are show in Table 4.22, indicate that, an experiment 7 the lower EWR (0.0122 mm²/min) with the greater S/N ratio (38.2728) is the peak current (22A), pulse-on time (95μs), pulse-off time (240μs) and servo voltage (95V).the weakest S/N ratio (15.1392) at experiment 4 with combination of peak current (15A), pulse-on time (95μs), pulse-off time (180μs) and servo voltage (105V). Therefore, the greater S/N ratio will corresponds to the better performance where the better performance for EWR is lower EWR.

From the experiment result and the analysis using the Minitab software, the response graph has been plot as shown in Figure 4.8.

Figure 4.8: Response graph for S/N ratio in EWR



From the graph and the table above, the response data can be represent the response table for the signal noise ratio by ranking each of the parameter after the analysis using the quality characteristics of the machining performance where need to be “Smaller the Better” as shows in Table 4.23. similar to other machining performance, from the graph show that the S/N ratio suggest that at peak current (level 2), pulse-on time (level 1), pulse-off time (level 2) and servo voltage (level 3) is the best level of parameter for the EWR.

Table 4.23: Response table for S/N ratio in EWR (Smaller the Better)

Level	Peak Current	Pulse-on Time	Pulse-off Time	Servo Voltage
1	33.49	28.76	31.88	32.05
2	25.88	30.32	26.37	33.82
3	33.93	34.22	35.06	27.43
Delta	8.05	5.46	8.69	6.39
Rank	1	4	2	3

From the design of experiment using the Taguchi method, the ANOVA also use for the EWR as mention before to get the contribution on (%) for each parameter that will conclude between the parameter which is the better parameter that can help in this experiment for EWR machining performance. The Table 4.24 shows the result:

Table 4.24: Table ANOVA for EWR

Parameter	DOF	Sum of square	Mean square	F	Contribution on (%)
Peak Current	2	0.00604	0.00302	1.23	29.0
Pulse-on Time	2	0.00418	0.00209	0.75	20.07
Pulse-off Time	2	0.00563	0.00281	1.11	27.03
Servo Voltage	2	0.00498	0.00249	0.94	23.67
TOTAL		0.02083			

The result of the ANOVA will also give the same result as the S/N ratio from the Figure 4.8 and Table 4.23. it is clear ANOVA data Table 4.24 the most contribution on machining parameter is pulse-off time (27.03%) and the lower contribution is pulse-on time (20,07%). Therefore, pulse-off time have the most effect to the EWR. Moreover, the value of the F-ratio also higher for the peak current which is 1.23 that prefer as the most significant factor.

Table 4.25: Regression coefficient of EWR

	Coefficient	SE coefficient	T	P-value	VIF

Constant	-0.1248	0.24881	-0.50	0.641	
Peak Current	-0.000038	0.003395	-0.01	0.992	1.000
Pulse-on Time	-0.0002945	0.0002796	-1.05	0.352	1.000
Pulse-off Time	-0.0000528	0.0003961	-0.13	0.900	1.000
Servo Voltage	-0.002400	0.002377	1.01	0.370	1.000
S= 0.0582133		R-Sq= 34.9%			
PRESS= 0.0759874		R-Sq(adj)= 0.0%			

From the result above, it can see that there is no parameters have the p-value less than 0.05, therefore it no significant for all parameter. The value of the R-square and the R-adjusted show that, it not properly explains the variation of the response value. Based on the table, the value of the R-square is (34.9%) and the R-adjusted is (0.0%). However, the result still can be determined the factor that peak current, pulse-on time, pulse-off time and servo voltage are significant in descending order.

4.3.3 Analysis of Surface Roughness (SR)

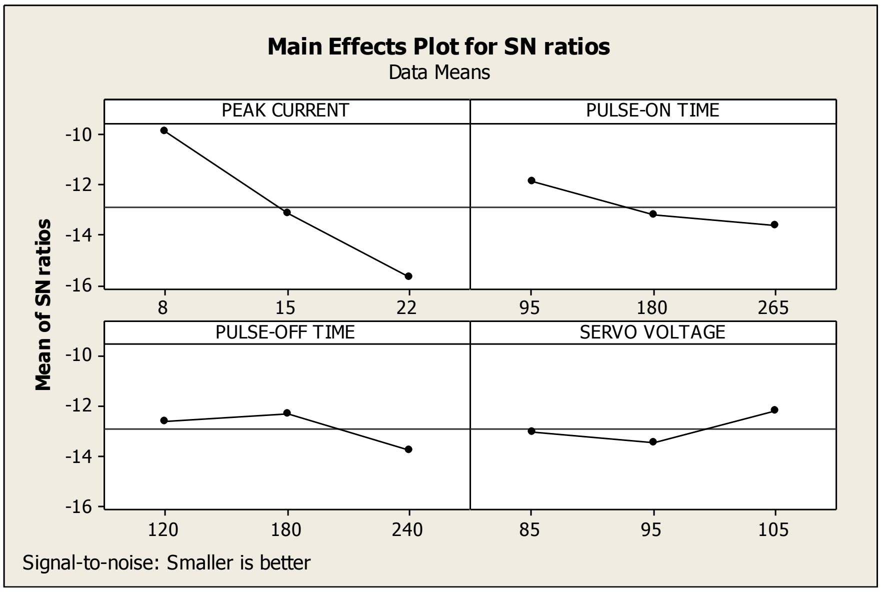
The last machining performance that will be optimum is the surface roughness (SR). The quality characteristics for the SR is same as the EWR where the “Smaller the Better” have been selected to get the good surface finish for the product. Therefore, from the result shows the S/N ratio of the SR and will choose the better data between 9 numbers of experiments in the table.

Table 4.26: Experiment data for S/N ratio in SR

Exp.No	SR (µm)	S/N ratio
1	2.7124	-8.6671
2	3.2576	-10.2580
3	3.4708	-10.8086
4	3.4811	-10.8343
5	5.2856	-14.4619
6	5.0843	-14.1246
7	6.3666	-16.0782
8	5.6230	-14.9994
9	6.2592	-15.9304

From the Table 4.26, the value of the S/N ratio response to the each parameter (peak current, pulse-on time, pulse-off time, servo voltage) have been plot during the analysis by using the same formula for EWR from the positive polarity. The best S/N ratio for the SR is -8.6671 at experiment 1 and also gives the lower SR that the better performances occur for the SR. study on table 2.26, the weakest S/N ratio is -16.078 for the experiment 7 with the combination of the peak current (22A), pulse-on time (95μs), pulse-off time (240μs) and servo voltage (95V) and the EWR also higher. Therefore it higher EWR is not suitable parameter level rather than lower EWR ant experiment 1. There are graph shows:

Figure 4.9: Response graph of S/N ratio in SR



The Table 4.25 shows the parameter will the different level and following with the rank. It represents the response table for the parameter according to the S/N ratio of the SR. From that, the most use during the experiment can be selected and prove the explanation on the ANOVA. From the figure above, the response graph for the SR show the S/N ratio where the S/N ratio for the SR is the smaller the better quality characteristics. Therefore, the S/N ratio suggest that at the peak current (level3), pulse-on time (level 3), pulse-off time (level 3) and servo voltage (level 2) is the best level of the parameter of the machining performance. The table below shows:

Table 4.25: Response table of S/N ratio in SR (Smaller the Better)

Level	Peak Current	Pulse-on Time	Pulse-off Time	Servo Voltage
1	-9.911	-11.860	-12.597	-13.020
2	-13.140	-13.240	-12.341	-13.487
3	-15.669	-13.621	-13.783	-12.214
Delta	5.758	1.761	1.442	1.273
Rank	1	2	3	4

The ANOVA for the SR have been analysis using the same software as others. The result have been show between the 4 parameter that used for the EDM experiment, which one the most give the higher contribution on(%) and the Table 4.29 below shows the data to make the comparison and selected the parameter for the SR.

Table 4.27: The ANOVA for SR

Parameter	DOF	Sum of square	Mean square	F	Contribution on (%)
Peak Current	2	12.930	6.465	15.01	83.37
Pulse-on Time	2	0.90	0.45	0.18	5.80
Pulse-off Time	2	0.84	0.42	0.17	5.42
Servo Voltage	2	0.84	0.42	0.17	5.42
TOTAL		15.51			

Based on the table above, the peak current was the maximum characteristics parameter contribution with 83.37%. The other parameter give the contribution with pulse-on time (5.80%), pulse-off time and servo voltage have the same percentage of contribution with 5.42%. moreover, the F-ratio for the peak current also give the higher contribution with 15.01 and it followed by pulse-on time with 0.18 at the second place.

Table 4.28: Regression coefficient of SR

	Coefficient	SE coefficient	T	P -value	VIF
Constant	2.486	1.885	1.32	0.258	
Peak Current	0.20971	0.02580	8.13	0.001	1.000
Pulse-on Time	0.004420	0.002124	2.08	0.106	1.000
Pulse-off Time	0.004731	0.003010	1.57	0.191	1.000

Servo Voltage	-0.02804	0.01806	-1.55	0.195	1.000
S= 0.442316		R-Sq= 95.0%			
PRESS= 3.91484		R-Sq(adj)= 89.9%			

Besides that, based on the p value, there is only one parameter that has p-value less than 0.05 which is peak current and the other 3 parameter has the P-value more than 0.05. Therefore, from the p-value for peak current is the most significant parameter rather than other and the percentage of contribution from above shows it influence the best SR result.

4.3.4 Regression Coefficient

Besides analysis the data from the experiment, the result also needs to come with the formula from the regression coefficient for the MRR, EWR and the SR. The equations for the machining performance will represent below. The formula will show the data comparison on Table 4.29, 4.30 and 4.31. The result also get by using the Minitab software and that will used for comparison data from the other data using another method. The methods that will be compared are Taguchi Method, RSM method and the actual data from the experiment.

MRR = 1.30 + 0.0414 peak current + 0.00108 pulse-on time + 0.00151 pulse-off time - 0.0198 servo voltage

EWR = - 0.125 - 0.00004 peak current - 0.000295 pulse-on time - 0.000053 pulse-off time + 0.00240 servo voltage

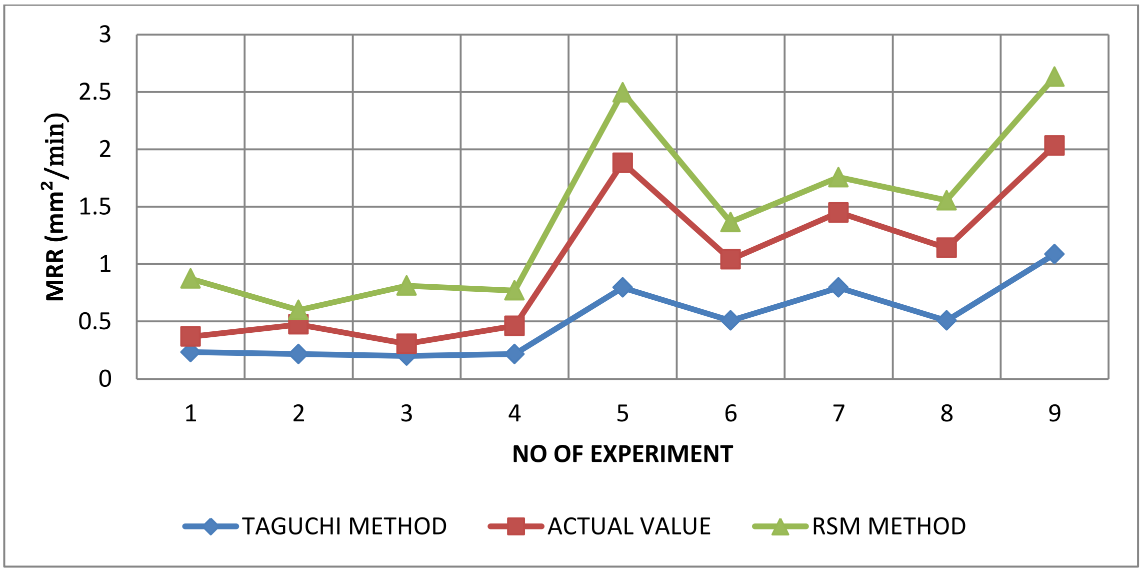
SR = 2.49 + 0.210 peak current + 0.00442 pulse-on time + 0.00473 pulse-off time - 0.0280 servo voltage

The comparisons between the 3 method for the MRR, EWR and SR also have been conducted for the negative copper (negative polarity). Using the formula from the regression coefficient for the MRR, EWR and SR, the comparison between the 3 method can be represented by substitute the value of the Taguchi method, RSM method which is well compared with the actual value of the experiment. For the negative copper, the data for the RSM method also take only 9 number of experiments for doing the comparison. Table shows the result:

Table 4.29: Result of MRR by comparing the value from different method

NO OF EXPERIMENT	TAGUCHI METHOD	ACTUAL VALUE	RSM METHOD
1	0.232	0.1352	0.5062
2	0.2164	0.2569	0.1258
3	0.2008	0.1048	0.5062
4	0.2164	0.2451	0.3082
5	0.7948	1.0869	0.6136
6	0.5074	0.5337	0.3238
7	0.7948	0.6548	0.3070
8	0.5074	0.6337	0.4142
9	1.0858	0.9470	0.5980

Figure 4.10: The material removal rate result between actual value, Taguchi method and RSM method

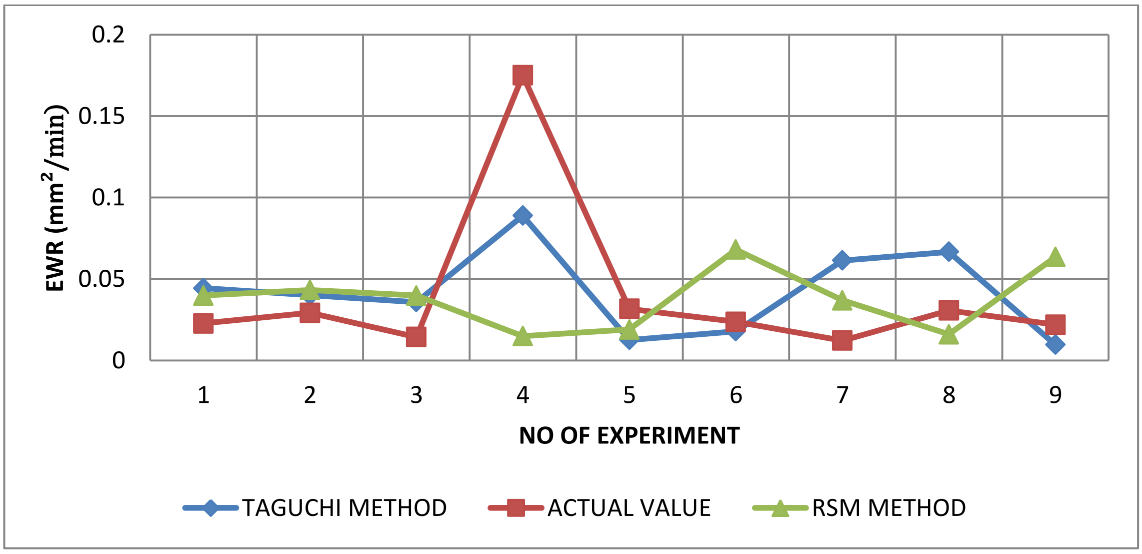


Based on the Figure 4.10 there are show that the RSM method gives the accurate and higher value of MRR rather than other method and actual value. This is because the higher MRR will give the better performance of the machining characteristics and the RSM method show the result that should get for the MRR. Otherwise, the Taguchi method show the lower value of MRR, therefore the method not been selected for the MRR.

Table 4.30: Result of EWR by comparing the value from different method

NO OF EXPERIMENT	TAGUCHI METHOD	ACTUAL VALUE	RSM METHOD
1	0.04430	0.0227	0.03976
2	0.04004	0.0292	0.04322
3	0.03579	0.0143	0.03976
4	0.08884	0.175	0.014963
5	0.01258	0.0316	0.01894
6	0.01787	0.0237	0.06802
7	0.06138	0.0122	0.03686
8	0.06666	0.0307	0.01604
9	0.009595	0.0219	0.06348

Figure 4.11: The electrode wear ratio between the actual value, Taguchi method and RSM method

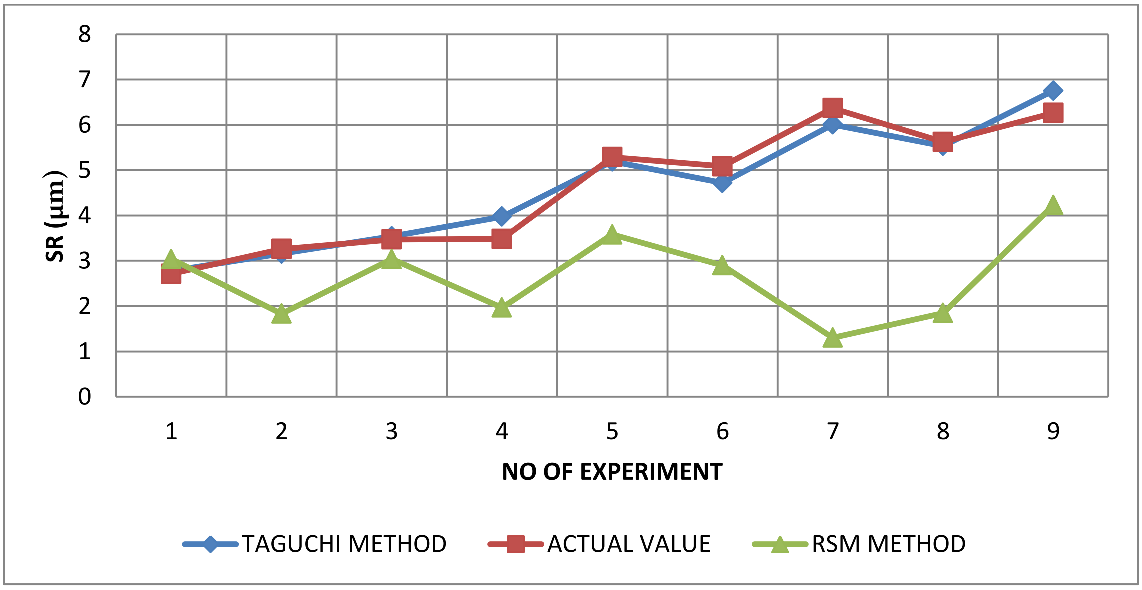


\In the Figure 4.11, the electrode wear ratio has been plot of the 3 method using same formulae. From the figure, there have 3 type lines that represent each method and the result show that the graph of the 3 methods not has so many different. The graph also shows that, the point for the RSM method of each experiment point at the lowest value rather than other. Therefore, the best method that been selected is RSM method this is because the EWR should be “Smaller the Better” and the graph show that the lower value of EWR have been at the RSM method.

Table 4.31: Result of SR by comparing the value from different method

NO OF EXPERIMENT	TAGUCHI METHOD	ACTUAL VALUE	RSM METHOD
1	2.7775	2.7124	3.0358
2	3.1570	3.2576	1.8310
3	3.5365	3.4708	3.0358
4	3.9713	3.4811	1.9678
5	5.1908	5.2856	3.5810
6	4.7189	5.0843	2.8990
7	6.0051	6.3666	1.3006
8	5.5332	5.6230	1.8458
9	6.7527	6.2592	4.2258

Figure 4.12: The surface roughness between the actual values, Taguchi method and RSM method



The comparison for the surface roughness (SR) also has been analysis. By make the comparison between the RSM method and the Taguchi method, the graph on the Figure 4.12 shows that the lower value from the 9 number of experiment for each method show the lowest value have represent by the RSM method and the higher value represent by Taguchi method. Otherwise, the machining characteristics of SR must be the" Smaller the Better" quality characteristics. Therefore, the chosen method for the negative copper analysis for SR is RSM method. From all tables above, the graph of the comparison method with the actual value have been plots for the EDM machining experiment. Figure 4.10, 4.11 and 4.12 shows the graph for the comparison that make by using the formula for the different method that have been analyses the best method of each machining characteristic (MRR, EWR and SR).

From the all analysis using the S/N ratio of the machining performance, the table response table for S/N ratio and the response graph for S/N ratio for the MRR, EWR and SR by using the positive and negative copper has been recorded for the analysis. The main effects that show from all S/N ratio graph give the influence of each level of the parameter on the machining performance. The table and graph of the S/N ratio also show the level having the major contribution are selected, from the graph and the optimized level for the particular parameter. The table state the rank of the parameter also based on the S/N ratio graph.

4.4 SUMMARY

From the chapter 4, the result and discussion the analyses have been done for negative and positive tool to select the best parameter level for the machining performance. Form the analysis the best result for the MRR, EWR and SR performance have been decide after discuss and analysis the table. Chapter 5 will give the detail result from the previous analysis and recommended best analysis for get better machining performance.

CHAPTER 5

CONCLUSION AND RECOMANDATION

5.1 CONCLUSION

A study on the EDM machining is performed by evaluating some machining parameter such as peak current, pulse-on time, pulse-off time and servo voltage it will respond to the MRR, EWR and SR. From the analysis, the better performance from the machining parameter will be chosen with the best level. The analysis is conducted from the run order by the Taguchi method.

The analysis occurs for the better performance with the best level for each parameter, regression coefficient and also the ANOVA will perform using Minitab 15 Software. Based on the analysis, it can conclude that the S/N ratio and the graph show will combine the best level of the parameter to get the higher MRR, lower EWR and better surface roughness.

Therefore, from the analysis that have done the best combination using the positive copper to perform the higher MRR with the parameter peak current (22A), pulse-on time (180µs), pulse-off time (180µs) and servo voltage (95V). For the minimum EWR, the combination of the parameter peak current (22A), pulse-on time (95µs), pulse-off time (240µs) and servo voltage (85V). Lastly, to obtain the better surface roughness the best parameter to give that performance with a peak current (22A), pulse-on time (180µs), pulse-off time (240µs) and servo voltage (95V).

The ANOVA analysis from the Minitab Software also gives the similar result that at each machining performance, the best and significant parameter is peak current. This is because of, from all machining performance the peak current is the most selected of contribution on with higher percentages. Therefore, the objective has been achieved.

The analyses for the negative copper also come with the best combination of the parameter to optimize the machining performance where for the higher MRR with the best combination of the parameter is at peak current (level 3), pulse-on time (level 2), pulse-off time (level 3) and servo voltage (level 1), the minimum EWR at peak current (level 2), pulse-on time (level 1), pulse-off time (level 2) and servo voltage (level 3) is the best level and for the minimum SR, the best combination at peak current (level3), pulse-on time (level 3), pulse-off time (level 3) and servo voltage (level 2) is the best level of the parameter of the machining performance.

The comparison between the Taguchi method, the actual data and RSM method is for defining the better method to get the better machining performance. There are comparable for the negative and positive copper which is the best method will provide the higher MRR, lower EWR and lower SR.

5.2 RECOMMENDATION

There are some recommendations to be considered to improving the detail of the project. The higher MRR is not always the most priority rather than another. However, higher MRR will give the rough surface roughness. Therefore, the parameter will give the effect and more research and study about other parameter should be selected to solve the problem.

Another recommendation for the future, the investigate of the machining performance should be consider other parameter to get better MRR, EWR and SR.

Therefore, other parameter such as machining depth, injection flushing, duty cycle and more should to investigate and defined the effect through by using that parameter.

Lastly, the suggestion that have to take it seriously is the difference of levels of parameter should be considered by using another level besides the level that have selected before. Therefore, the each level will improve the quality in the EDM process.

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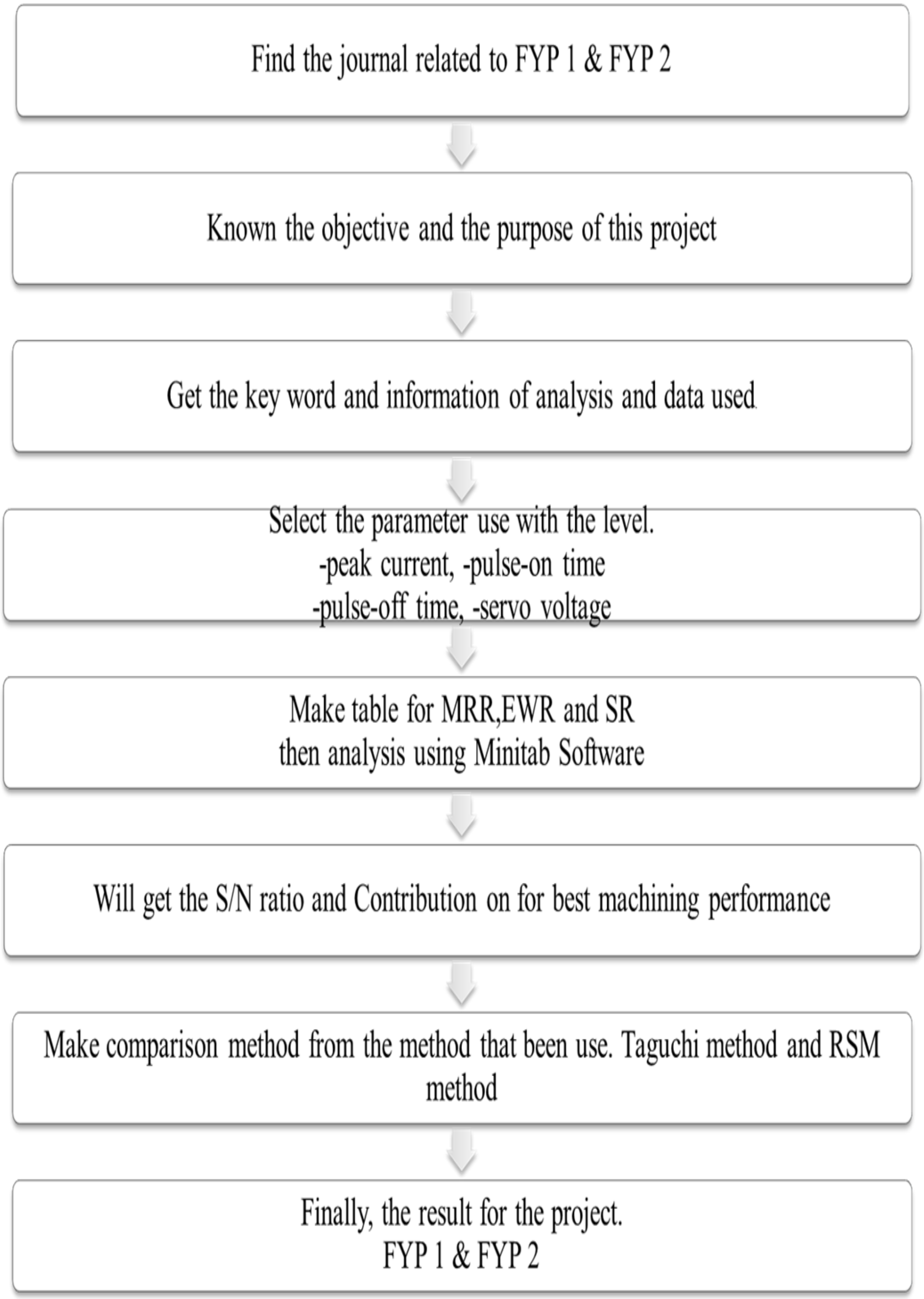
APPENDIX A1: Gantt Chart for Final Year Project 1

NO	MONTH 2012	SEPTEMBER		OCTOBER					NOVEMBER				DECEMBER		
	DATE	18	26	3	10	17	22	31	7	14	21	28	5	12	20
	TITLE														
1	**INTRODUCTION**														
	ABSTRACT														
	ACKNOWELDGEMENT														
2	**CHAPTER 1**														
	INTRODUCTION									CUTI SEMESTER					
	PROBLEM STATEMENT														
	OBJECTIVE														
	SIGNIFICANCE OF RESEARCH														
	SCOPE OF WORK														
	EXPECTED RESULT														
	GANTT CHART														
3	**CHAPTER 2**														
	LITERATURE REVIEW														
	READING JOURNAL														
	COLLECTING INFORMATION														
	SUMMARY OF JOURNAL														
4	**CHAPTER 3**														
	METHODOLOGY														
	SAMPLE PROPERTIES														
	EXPERIMENT METHOD														
	MATERIAL														
	FORMULA														
5	**CHAPTER 4**														
	CONCLUSION														
	PRESENTATION FYP														

APPENDIX A2: Gantt Chart for Final Year Project 2

NO	WEEK	WEEK 1	WEEK 2	WEEK 3	WEEK 4	WEEK 5	WEEK 6	WEEK 7	WEEK 8	WEEK 9	WEEK 10	WEEK 11	WEEK 12	WEEK 13	WEEK 14	WEEK 15
	TITLE															
1	**ANALYSIS SETUP**															
	COLLECTING DATA	■	■													
	DEFINED PARAMETER AND LEVEL	■	■													
	MINITAB SOFTWARE FOR ANALYSIS	■	■	■	■	■	■	■	■	■	■	■	■			
2	**DOE(DESIGN OF EXPERIMENT)**															
	TAGUCHI METHOD	■	■	■												
	ANOVA	■	■	■												
	REGRESSION COEFFICIENT	■	■	■												
	COMPARE WITH RSM METHOD	■	■	■												
3	**RESULT AND DISCUSION**															
	ANALYSIS FOE POSITIVE COPPER				■	■	■	■	■	■	■	■	■			
	ANALYSIS FOR NEGATIVE COPPER				■	■	■	■	■	■	■	■	■			
	REGRESSION COEFFICIENT FOR BOTH				■	■	■	■	■	■	■	■	■			
	COMPARISON BETWEEN METHOD				■	■	■	■	■	■	■	■	■			
	DECIDE BEST CHOICE										■	■	■			
4	**CONCLUSION**															
	THE BEST MACHINING PERFORMANCE FOR NEGATIVE AND POSITIVE TOOL												■	■		
	BEST METHOD USE												■	■		
5	**RECOMMENDATION**															
	IMPROVEMENT CAN BEEN DONE													■		
	PRESENTATION FYP														■	
6	**REPORT**															
	SUBMIT REPORT															■

APPENDIX A3: Progress flow of the FYP project



APPENDIX B1: Positive Copper Analysis

Welcome to Minitab, press F1 for help.

Taguchi Design

Taguchi Orthogonal Array Design

L9(3**4)

Factors: 4
Runs: 9

Columns of L9(3**4) Array

1 2 3 4

Taguchi Analysis: MRR versus PEAK CURRENT, PULSE-ON TIM, PULSE-OFF TI, …

* NOTE * Unable to perform linear model analysis.

Response Table for Signal to Noise Ratios
Larger is better

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	-9.8748	-4.9890	-5.2496	-5.8684
2	-5.3459	-4.5369	-3.1952	-2.9588
3	-0.4441	-6.1389	-7.2201	-6.8377
Delta	9.4306	1.6020	4.0249	3.8789
Rank	1	4	2	3

Response Table for Means

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	0.3547	0.6310	0.5949	0.5794
2	0.5473	0.6169	0.7176	0.7346
3	0.9530	0.6071	0.5426	0.5410
Delta	0.5983	0.0238	0.1750	0.1936
Rank	1	4	3	2

Main Effects Plot for Means

Main Effects Plot for SN ratios

Taguchi Analysis: EWR versus PEAK CURRENT, PULSE-ON TIM, PULSE-OFF TI, …

Response Table for Signal to Noise Ratios
Smaller is better

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	28.90	37.05	35.60	26.27
2	60.93	42.27	56.28	48.81
3	28.71	39.22	26.66	43.46
Delta	32.21	5.22	29.62	22.54
Rank	1	4	2	3

Response Table for Means

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	0.149333	0.138837	0.123400	0.127200
2	0.004603	0.013700	0.008903	0.025033
3	0.041733	0.043133	0.063367	0.043437
Delta	0.144730	0.125137	0.114497	0.102167
Rank	1	2	3	4

Main Effects Plot for Means

Main Effects Plot for SN ratios

Taguchi Analysis: SR versus PEAK CURRENT, PULSE-ON TIM, PULSE-OFF TI, …

Response Table for Signal to Noise Ratios
Smaller is better

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	-8.914	-10.741	-9.776	-11.471
2	-11.238	-12.265	-12.013	-11.931
3	-14.220	-11.366	-12.583	-10.970
Delta	5.305	1.524	2.807	0.960
Rank	1	3	2	4

Response Table for Means

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	2.847	3.732	3.219	4.038
2	3.696	4.135	4.088	4.093
3	5.172	3.848	4.408	3.584
Delta	2.325	0.403	1.190	0.509
Rank	1	4	2	3

Main Effects Plot for Means

Main Effects Plot for SN ratios

Regression Analysis: MRR versus PEAK CURRENT, PULSE-ON TIME, …

```
The regression equation is
MRR = 0.263 + 0.0427 PEAK CURRENT - 0.000140 PULSE-ON TIME
      - 0.00044 PULSE-OFF TIME - 0.00192 SERVO VOLTAGE
```

Predictor	Coef	SE Coef	T	P	VIF
Constant	0.2632	0.7620	0.35	0.747	
PEAK CURRENT	0.04274	0.01043	4.10	0.015	1.000
PULSE-ON TIME	-0.0001402	0.0008587	-0.16	0.878	1.000
PULSE-OFF TIME	-0.000436	0.001216	-0.36	0.738	1.000
SERVO VOLTAGE	-0.001918	0.007299	-0.26	0.806	1.000

S = 0.178782   R-Sq = 81.0%   R-Sq(adj) = 61.9%

PRESS = 0.580092   R-Sq(pred) = 13.67%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	4	0.54411	0.13603	4.26	0.095
Residual Error	4	0.12785	0.03196		
Total	8	0.67196			

Durbin-Watson statistic = 2.56016

Residual Plots for MRR

Regression Analysis: EWR versus PEAK CURRENT, PULSE-ON TIME, …

```
The regression equation is
EWR = 0.770 - 0.00769 PEAK CURRENT - 0.000563 PULSE-ON TIME
      - 0.000500 PULSE-OFF TIME - 0.00419 SERVO VOLTAGE
```

Predictor	Coef	SE Coef	T	P	VIF
Constant	0.7698	0.4766	1.62	0.182	
PEAK CURRENT	-0.007686	0.006522	-1.18	0.304	1.000
PULSE-ON TIME	-0.0005630	0.0005371	-1.05	0.354	1.000
PULSE-OFF TIME	-0.0005003	0.0007609	-0.66	0.547	1.000
SERVO VOLTAGE	-0.004188	0.004565	-0.92	0.411	1.000

S = 0.111831   R-Sq = 48.5%   R-Sq(adj) = 0.0%

PRESS = 0.524358   R-Sq(pred) = 0.00%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	4	0.04704	0.01176	0.94	0.523
Residual Error	4	0.05002	0.01251		
Total	8	0.09706			

Durbin-Watson statistic = 2.76525

Residual Plots for EWR

Regression Analysis: SR versus PEAK CURRENT, PULSE-ON TIME, …

The regression equation is
SR = 1.67 + 0.166 PEAK CURRENT + 0.00068 PULSE-ON TIME + 0.00991 PULSE-OFF TIME
- 0.0227 SERVO VOLTAGE

Predictor	Coef	SE Coef	T	P	VIF
Constant	1.665	1.839	0.91	0.416	
PEAK CURRENT	0.16607	0.02516	6.60	0.003	1.000
PULSE-ON TIME	0.000680	0.002072	0.33	0.759	1.000
PULSE-OFF TIME	0.009914	0.002935	3.38	0.028	1.000
SERVO VOLTAGE	-0.02272	0.01761	-1.29	0.267	1.000

S = 0.431419   R-Sq = 93.4%   R-Sq(adj) = 86.8%

PRESS = 3.18145   R-Sq(pred) = 71.86%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	4	10.5611	2.6403	14.19	0.012
Residual Error	4	0.7445	0.1861		
Total	8	11.3056			

Durbin-Watson statistic = 2.34185

Residual Plots for SR

One-way ANOVA: MRR versus PEAK CURRENT

Source	DF	SS	MS	F	P
PEAK CURRENT	2	0.5596	0.2798	14.95	0.005
Error	6	0.1123	0.0187		
Total	8	0.6720			

S = 0.1368   R-Sq = 83.28%   R-Sq(adj) = 77.71%

```
                          Individual 95% Cis For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  ----+---------+---------+---------+-----
 8     3  0.3547  0.1941  (-------*-------)
15     3  0.5473  0.1033          (-------*-------)
22     3  0.9530  0.0885                          (-------*-------)
                          ----+---------+---------+---------+-----
                            0.25      0.50      0.75      1.00
```

Pooled StDev = 0.1368

Individual Value Plot of MRR vs PEAK CURRENT

Normplot of Residuals for MRR

One-way ANOVA: PULSE-ON TIME versus PEAK CURRENT

```
Source        DF     SS    MS     F      P
PEAK CURRENT   2      0     0  0.00  1.000
Error          6  43350  7225
Total          8  43350

S = 85   R-Sq = 0.00%   R-Sq(adj) = 0.00%


                         Individual 95% Cis For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  -+---------+---------+---------+--------
 8     3  180.00  85.00  (----------------*----------------)
15     3  180.00  85.00  (----------------*----------------)
22     3  180.00  85.00  (----------------*----------------)
                         -+---------+---------+---------+--------
                         70       140       210       280

Pooled StDev = 85.00
```

Individual Value Plot of PULSE-ON TIME vs PEAK CURRENT

Residual Plots for PULSE-ON TIME

One-way ANOVA: MRR versus PULSE-ON TIME

```
Source         DF     SS     MS     F      P
PULSE-ON TIME   2  0.001  0.000  0.00  0.996
Error           6  0.671  0.112
Total           8  0.672

S = 0.3344   R-Sq = 0.13%   R-Sq(adj) = 0.00%


                          Individual 95% Cis For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  -----+---------+---------+---------+----
 95    3  0.6310  0.3532   (------------------*------------------)
180    3  0.6169  0.2139   (------------------*------------------)
265    3  0.6071  0.4063  (------------------*------------------)
                          -----+---------+---------+---------+----
                             0.25      0.50      0.75      1.00

Pooled StDev = 0.3344
```

Individual Value Plot of MRR vs PULSE-ON TIME

Residual Plots for MRR

APPENDIX B2: Negative Copper Analysis

Welcome to Minitab, press F1 for help.

Taguchi Design

Taguchi Orthogonal Array Design

L9(3**4)

Factors: 4
Runs: 9

Columns of L9(3**4) Array

1 2 3 4

Taguchi Analysis: MRR versus PEAK CURRENT, PULSE-ON TIM, PULSE-OFF TI, ...

Response Table for Signal to Noise Ratios
Larger is better

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	-16.259	-11.090	-8.932	-5.710
2	-5.648	-5.014	-8.164	-6.979
3	-2.704	-8.507	-7.516	-11.923
Delta	13.555	6.076	1.417	6.213
Rank	1	3	4	2

Response Table for Means

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	0.1656	0.3450	0.4342	0.7230
2	0.6219	0.6592	0.4830	0.4818
3	0.7452	0.5285	0.6155	0.3279
Delta	0.5795	0.3141	0.1813	0.3952
Rank	1	3	4	2

Main Effects Plot for Means

Main Effects Plot for SN ratios

Taguchi Analysis: EWR versus PEAK CURRENT, PULSE-ON TIM, PULSE-OFF TI, ...

Response Table for Signal to Noise Ratios
Smaller is better

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	33.49	28.76	31.88	32.05

2	25.88	30.32	26.37	33.82
3	33.93	34.22	35.06	27.43
Delta	8.05	5.46	8.69	6.39
Rank	2	4	1	3

Response Table for Means

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	0.02207	0.06997	0.02570	0.02533
2	0.07677	0.03050	0.07530	0.02170
3	0.02153	0.01990	0.01937	0.07333
Delta	0.05523	0.05007	0.05593	0.05163
Rank	2	4	1	3

Main Effects Plot for Means

Main Effects Plot for SN ratios

Taguchi Analysis: EWR versus PEAK CURRENT, PULSE-ON TIM, PULSE-OFF TI, ...

Response Table for Signal to Noise Ratios
Smaller is better

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	33.49	28.76	31.88	32.05
2	25.88	30.32	26.37	33.82
3	33.93	34.22	35.06	27.43
Delta	8.05	5.46	8.69	6.39
Rank	2	4	1	3

Response Table for Means

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	0.02207	0.06997	0.02570	0.02533
2	0.07677	0.03050	0.07530	0.02170
3	0.02153	0.01990	0.01937	0.07333
Delta	0.05523	0.05007	0.05593	0.05163
Rank	2	4	1	3

Main Effects Plot for Means

Main Effects Plot for SN ratios

Taguchi Analysis: SR versus PEAK CURRENT, PULSE-ON TIM, PULSE-OFF TI, ...

Response Table for Signal to Noise Ratios
Smaller is better

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	-9.911	-11.860	-12.597	-13.020
2	-13.140	-13.240	-12.341	-13.487

3	-15.669	-13.621	-13.783	-12.214
Delta	5.758	1.761	1.442	1.273
Rank	1	2	3	4

Response Table for Means

Level	PEAK CURRENT	PULSE-ON TIME	PULSE-OFF TIME	SERVO VOLTAGE
1	3.147	4.187	4.473	4.752
2	4.617	4.722	4.333	4.903
3	6.083	4.938	5.041	4.192
Delta	2.936	0.751	0.708	0.711
Rank	1	2	4	3

Main Effects Plot for Means

Main Effects Plot for SN ratios

5/16/2013 9:09:38 AM

Welcome to Minitab, press F1 for help.
Retrieving project from file: 'C:\USERS\USER\DESKTOP\MINITAB.MPJ (SECOND DATA).MPJ'

One-way ANOVA: MRR versus PEAK CURRENT

Source	DF	SS	MS	F	P
PEAK CURRENT	2	0.5592	0.2796	3.81	0.085
Error	6	0.4403	0.0734		
Total	8	0.9995			

S = 0.2709   R-Sq = 55.95%   R-Sq(adj) = 41.27%

```
                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level  N    Mean   StDev  ------+---------+---------+---------+---
 8     3  0.1656  0.0805  (----------*----------)
15     3  0.6219  0.4278              (----------*----------)
22     3  0.7452  0.1751                 (----------*----------)
                          ------+---------+---------+---------+---
                              0.00      0.35      0.70      1.05
```

Pooled StDev = 0.2709

Residual Plots for MRR

One-way ANOVA: MRR versus PULSE-ON TIME

Source	DF	SS	MS	F	P
PULSE-ON TIME	2	0.149	0.075	0.53	0.615
Error	6	0.850	0.142		
Total	8	0.999			

S = 0.3764   R-Sq = 14.95%   R-Sq(adj) = 0.00%

Individual 95% CIs For Mean Based on

```
                                 Pooled StDev
Level  N    Mean   StDev  -----+---------+---------+---------+----
 95    3  0.3450  0.2738  (--------------*--------------)
180    3  0.6592  0.4156           (--------------*--------------)
265    3  0.5285  0.4211       (--------------*--------------)
                          -----+---------+---------+---------+----
                             0.00      0.35      0.70      1.05

Pooled StDev = 0.3764
```

Residual Plots for MRR

One-way ANOVA: MRR versus PULSE-OFF TIME

Source	DF	SS	MS	F	P
PULSE-OFF TIME	2	0.053	0.026	0.17	0.850
Error	6	0.947	0.158		
Total	8	0.999			

S = 0.3972   R-Sq = 5.28%   R-Sq(adj) = 0.00%

```
                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  ----+---------+---------+---------+-----
120    3  0.4342  0.2637  (---------------*---------------)
180    3  0.4830  0.4019    (---------------*---------------)
240    3  0.6155  0.4922        (---------------*---------------)
                          ----+---------+---------+---------+-----
                            0.00      0.35      0.70      1.05

Pooled StDev = 0.3972
```

Residual Plots for MRR

One-way ANOVA: MRR versus SERVO VOLTAGE

Source	DF	SS	MS	F	P
SERVO VOLTAGE	2	0.238	0.119	0.94	0.442
Error	6	0.761	0.127		
Total	8	0.999			

S = 0.3562   R-Sq = 23.82%   R-Sq(adj) = 0.00%

```
                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  ----+---------+---------+---------+-----
 85    3  0.7230  0.5139           (-------------*------------)
 95    3  0.4818  0.2040     (-------------*------------)
105    3  0.3279  0.2740  (------------*------------)
                          ----+---------+---------+---------+-----
                            0.00      0.40      0.80      1.20

Pooled StDev = 0.3562
```

Residual Plots for MRR

One-way ANOVA: EWR versus PEAK CURRENT

```
Source        DF       SS       MS     F      P
PEAK CURRENT   2  0.00604  0.00302  1.23  0.358
Error          6  0.01479  0.00246
Total          8  0.02083

S = 0.04965   R-Sq = 29.01%   R-Sq(adj) = 5.35%


                            Individual 95% CIs For Mean Based on Pooled StDev
Level  N     Mean    StDev     +---------+---------+---------+---------
 8     3  0.02207  0.00747     (-------------*-------------)
15     3  0.07677  0.08516                (-------------*-------------)
22     3  0.02153  0.00925     (-------------*-------------)
                               +---------+---------+---------+---------
                            -0.050     0.000     0.050     0.100

Pooled StDev = 0.04965
```

Residual Plots for EWR

One-way ANOVA: EWR versus PULSE-ON TIME

```
Source         DF       SS       MS     F      P
PULSE-ON TIME   2  0.00418  0.00209  0.75  0.511
Error           6  0.01666  0.00278
Total           8  0.02083

S = 0.05269   R-Sq = 20.05%   R-Sq(adj) = 0.00%


                            Individual 95% CIs For Mean Based on Pooled StDev
Level  N     Mean    StDev    -+---------+---------+---------+--------
 95    3  0.06997  0.09111              (---------------*---------------)
180    3  0.03050  0.00121      (---------------*---------------)
265    3  0.01990  0.00495    (---------------*---------------)
                              -+---------+---------+---------+--------
                            -0.050     0.000     0.050     0.100

Pooled StDev = 0.05269
```

Residual Plots for EWR

One-way ANOVA: EWR versus PULSE-OFF TIME

```
Source          DF       SS       MS     F      P
PULSE-OFF TIME   2  0.00563  0.00281  1.11  0.389
Error            6  0.01520  0.00253
Total            8  0.02083

S = 0.05034   R-Sq = 27.02%   R-Sq(adj) = 2.69%


                            Individual 95% CIs For Mean Based on Pooled StDev
Level  N     Mean    StDev     +---------+---------+---------+---------
120    3  0.02570  0.00436      (-------------*-------------)
180    3  0.07530  0.08642                (-------------*-------------)
240    3  0.01937  0.01065     (-------------*-------------)
                               +---------+---------+---------+---------
```

```
                               -0.050    0.000     0.050     0.100

Pooled StDev = 0.05034
```

Residual Plots for EWR

One-way ANOVA: EWR versus SERVO VOLTAGE

```
Source         DF       SS       MS     F      P
SERVO VOLTAGE   2  0.00498  0.00249  0.94  0.440
Error           6  0.01585  0.00264
Total           8  0.02083

S = 0.05139   R-Sq = 23.92%   R-Sq(adj) = 0.00%


                            Individual 95% CIs For Mean Based on Pooled StDev
Level  N     Mean    StDev     +---------+---------+---------+---------
 85    3  0.02533  0.00545      (-------------*--------------)
 95    3  0.02170  0.00867     (-------------*--------------)
105    3  0.07333  0.08843               (--------------*-------------)
                               +---------+---------+---------+---------
                            -0.050     0.000     0.050     0.100

Pooled StDev = 0.05139
```

Residual Plots for EWR

One-way ANOVA: SR versus PEAK CURRENT

```
Source        DF      SS     MS      F      P
PEAK CURRENT   2  12.930  6.465  15.01  0.005
Error          6   2.585  0.431
Total          8  15.515

S = 0.6563   R-Sq = 83.34%   R-Sq(adj) = 77.79%


                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  --+---------+---------+---------+-------
 8     3  3.1469  0.3911  (-------*-------)
15     3  4.6170  0.9889               (------*-------)
22     3  6.0829  0.4019                           (-------*------)
                          --+---------+---------+---------+-------
                          2.4       3.6       4.8       6.0

Pooled StDev = 0.6563
```

Residual Plots for SR

One-way ANOVA: SR versus PULSE-ON TIME

```
Source         DF     SS    MS     F      P
PULSE-ON TIME   2   0.90  0.45  0.18  0.836
Error           6  14.62  2.44
Total           8  15.51
```

```
S = 1.561   R-Sq = 5.79%   R-Sq(adj) = 0.00%


                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level  N   Mean  StDev  -------+---------+---------+---------+--
 95    3  4.187  1.927  (--------------*--------------)
180    3  4.722  1.279      (-------------*--------------)
265    3  4.938  1.400       (--------------*--------------)
                        -------+---------+---------+---------+--
                             3.0       4.5       6.0       7.5

Pooled StDev = 1.561
```

Residual Plots for SR

One-way ANOVA: SR versus PULSE-OFF TIME

Source	DF	SS	MS	F	P
PULSE-OFF TIME	2	0.84	0.42	0.17	0.846
Error	6	14.67	2.45		
Total	8	15.51			

```
S = 1.564   R-Sq = 5.44%   R-Sq(adj) = 0.00%


                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level  N   Mean  StDev  ------+---------+---------+---------+---
120    3  4.473  1.549   (--------------*--------------)
180    3  4.333  1.672  (--------------*--------------)
240    3  5.041  1.463       (--------------*-------------)
                        ------+---------+---------+---------+---
                            3.0       4.5       6.0       7.5

Pooled StDev = 1.564
```

Residual Plots for SR

One-way ANOVA: SR versus SERVO VOLTAGE

Source	DF	SS	MS	F	P
SERVO VOLTAGE	2	0.84	0.42	0.17	0.846
Error	6	14.67	2.45		
Total	8	15.51			

```
S = 1.564   R-Sq = 5.43%   R-Sq(adj) = 0.00%


                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level  N   Mean  StDev  -------+---------+---------+---------+--
 85    3  4.752  1.833      (--------------*-------------)
 95    3  4.903  1.562       (--------------*-------------)
105    3  4.192  1.240  (--------------*--------------)
                        -------+---------+---------+---------+--
                             3.0       4.5       6.0       7.5

Pooled StDev = 1.564
```

Residual Plots for SR

Regression Analysis: MRR versus PEAK CURRENT, PULSE-ON TIME, ...

```
The regression equation is
MRR = 1.30 + 0.0414 PEAK CURRENT + 0.00108 PULSE-ON TIME
      + 0.00151 PULSE-OFF TIME - 0.0198 SERVO VOLTAGE
```

Predictor	Coef	SE Coef	T	P	VIF
Constant	1.3008	0.8569	1.52	0.204	
PEAK CURRENT	0.04140	0.01173	3.53	0.024	1.000
PULSE-ON TIME	0.0010792	0.0009656	1.12	0.326	1.000
PULSE-OFF TIME	0.001511	0.001368	1.10	0.331	1.000
SERVO VOLTAGE	-0.019758	0.008208	-2.41	0.074	1.000

```
S = 0.201048   R-Sq = 83.8%   R-Sq(adj) = 67.6%

PRESS = 1.05933   R-Sq(pred) = 0.00%
```

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	4	0.83782	0.20945	5.18	0.070
Residual Error	4	0.16168	0.04042		
Total	8	0.99950			

```
No replicates.
Cannot do pure error test.

Durbin-Watson statistic = 2.23875
```

Residual Plots for MRR

Regression Analysis: EWR versus PEAK CURRENT, PULSE-ON TIME, ...

```
The regression equation is
EWR = - 0.125 - 0.00004 PEAK CURRENT - 0.000295 PULSE-ON TIME
      - 0.000053 PULSE-OFF TIME + 0.00240 SERVO VOLTAGE
```

Predictor	Coef	SE Coef	T	P	VIF
Constant	-0.1248	0.2481	-0.50	0.641	
PEAK CURRENT	-0.000038	0.003395	-0.01	0.992	1.000
PULSE-ON TIME	-0.0002945	0.0002796	-1.05	0.352	1.000
PULSE-OFF TIME	-0.0000528	0.0003961	-0.13	0.900	1.000
SERVO VOLTAGE	0.002400	0.002377	1.01	0.370	1.000

```
S = 0.0582133   R-Sq = 34.9%   R-Sq(adj) = 0.0%

PRESS = 0.0759874   R-Sq(pred) = 0.00%
```

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	4	0.007277	0.001819	0.54	0.719

Residual Error	4	0.013555	0.003389
Total	8	0.020832	

No replicates.
Cannot do pure error test.

Durbin-Watson statistic = 1.78802

Residual Plots for EWR

Regression Analysis: SR versus PEAK CURRENT, PULSE-ON TIME, ...

The regression equation is
SR = 2.49 + 0.210 PEAK CURRENT + 0.00442 PULSE-ON TIME + 0.00473 PULSE-OFF TIME
- 0.0280 SERVO VOLTAGE

Predictor	Coef	SE Coef	T	P	VIF
Constant	2.486	1.885	1.32	0.258	
PEAK CURRENT	0.20971	0.02580	8.13	0.001	1.000
PULSE-ON TIME	0.004420	0.002124	2.08	0.106	1.000
PULSE-OFF TIME	0.004731	0.003010	1.57	0.191	1.000
SERVO VOLTAGE	-0.02804	0.01806	-1.55	0.195	1.000

S = 0.442316   R-Sq = 95.0%   R-Sq(adj) = 89.9%

PRESS = 3.91484   R-Sq(pred) = 74.77%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	4	14.7323	3.6831	18.83	0.007
Residual Error	4	0.7826	0.1956		
Total	8	15.5148			

No replicates.
Cannot do pure error test.

Durbin-Watson statistic = 1.35841

Residual Plots for SR