MULTIPLE OBJECTIVE OPTIMIZATION OF ELECTRICAL DISCHARGE MACHINING ON TITANIUM ALLOY USING GREY RELATIONAL ANALYSIS

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MUHAMMAD ALIFF NAZREEN BIN NORAZMI

Thesis submitted in partial fulfilment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering with Manufacturing Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

JUNE 2012

UNIVERSITI MALAYSIA PAHANG
FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled "*Multiple Objective Optimization of Electrical Discharge Machining On Titanium Alloy Using Grey Relation Analysis*" is written by *Muhammad Aliff Nazreen Bin Norazmi* . I have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfilment of the requirements for the degree of Bachelor of Mechanical Engineering with Manufacturing Engineering.

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I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

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Dedicated to my beloved parents Norazmi Bin Berahim and Wan Rosmarini Bt Mohamed for their love and support in my life.

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In the name of Allah, the Most Gracious and Most Compassionate

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ABSTRACT

This report deals with the machining workpiece Titanium Alloy using electrical discharge machining (EDM). The objective of this thesis is to optimize the surface roughness (SR), electrode wear ratio (EWR) and material removal rate (MRR) by using grey relational analysis (GRA) with orthogonal array (OA) and to discuss on the significant result by using Analysis of Variance (ANOVA). The machining of Titanium Alloy workpiece was performed using the EDM machine AQ55L (ATC) and the analysis done using equation for GRA and STATISTICA software for ANOVA. In this study, the machining parameters, namely workpiece polarity, pulse off time, pulse on time, peak current and servo voltage are optimized. A grey relational grade obtained from the grey relational analysis is used to solve the EDM process with the multiple performance characteristics. Optimal machining parameters can then be determined by the grey relational grade as the performance index. Based from the result, the most significant parameter that affects the MRR, EWR and SR was the peak current while significant parameter was pulse off time. Experimental results have shown that machining performance in the EDM process can be improved effectively through this approach.

ABSTRAK

Laporan ini membincangkan proses pemesinan aloi titanium menggunakan proses pemesinan nyahcas elektrik (EDM). Objektif tesis ini adalah untuk mengoptimumkan kekasaran permukaan (SR), nisbah kehausan elektrod (EWR), dan kadar penyingkiran (MRR) dengan menggunakan analisis hubungan kelabu (GRA) dengan susunan orthogonal (OA) dan membincangkan keputusan yang signifikan menggunakan analisis perbezaan (ANOVA). Kerja pemesinan aloi titanium dilakukan menggunakan mesin AQ55L (ATC) dan analisis menggunakan persamaan bagi GRA dan perisian STATISTICA untuk ANOVA. Dalam kajian ini, parameter memesin iaitu kekutuban keluli kerja, pulse off time, pulse on time, arus puncak dan servo voltan yang dioptimumkan. Gred hubungan kelabu didapati daripada analisis hubungan kelabu digunakan untuk menyelesaikan pelbagai proses ciri-ciri prestasi. Parameter memesin optimum boleh ditentukan dengan gred hubungan kelabu sebagai indeks prestasi. Daripada keputusan, parameter paling signifikan yang member kesan kepada MRR, EWR and SR adalah arus puncak manakala signifikan parameter adalah pulse off time. Keputusan eksperimen telah menunjukkan bahawa prestasi memesin boleh ditingkatkan dengan efektif melalui kaedah ini.

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t_i	Pulse On-time
t_o	Pulse Off-time
µs	The duration of time machining
µΩ	Electrical resistivity
s	second
W_b	Weight of workpiece material before machining (g)
W_a	Weight of workpiece material after machining (g)
A	Ampere
µm	Micrometer
x_{ij}	Normalized value
x_i^0	Ideal value
ζ	Distinguishing coefficient
γ_m	Total mean of the Grey relational grade
γ_i	Mean of the Grey relational grade at optimal level
q	Number of the machining parameters

List of Abbreviations

EDM	Electrical Discharge Machining
MRR	Material Removal Rate
EWR	Electrode Wear Ratio
V	Voltage
I	Current
SME	Society of Manufacturing Engineering
GRA	Grey Relational Analysis
OA	Orthogonal Array
DOE	Design of Experiment
EWW	Weight of Electrode Use
WRW	Weight of Workpiece Used
ANOVA	Analysis of Variance
GRG	Grey Relational Grade
GRC	Grey Relational Coefficient
MS	Mean Square
D.O.F	Degree of Freedom
SS	Sum of Square
F	Fisher Test

CHAPTER 1

INTRODUCTION

1.1 Introduction

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

The machine used in this study is a AQ55L (ATC) EDM and the workpiece material used is a Titanium Alloy. The important output parameters of the process are the material removal rate (MRR), electrode wear ratio (EWR) and surface roughness (SR). Grey Relational Analysis (GRA) is a method that used to get the desired information based on the relation with incomplete information. GRA require only a limited amount of data to estimate behavior of unknown systems. Lin (1998) presented the use of Grey relational grade to the machining parameters optimization of the electrical discharge machining (EDM) process. By using this method, we can determine and find the suitable parameter to optimize the electrical discharge machine on mild steel workpiece. This project is to investigate the optimum parameter required for MRR, EWR and SR by using GRA.

1.2 Importance of research

- **i.** Improve the quality surface finish of the cut metal.
- **ii.** Improve efficiency of production process.
- **iii.** Minimize the cost of production process.
- **iv.** Enhance the production rate.

1.3 Objective

- **i.** Optimize material removal rate (MRR), electrode wear ratio (EWR) and the surface roughness (SR), by using GRA with Orthogonal Array (OA).
- **ii.** Discuss on the significant result by using analysis of variance (ANOVA).

1.4 Problem statement

During the machining process, wear will occur on the electrode. This will affect the efficiency of the machining process and cost during the machining. Thus, to avoid wear and reduce cost, the optimum parameter on the MRR, EWR and SR must be obtain. The optimum parameter will optimize the usage of machine.

1.5 Project Scopes

This project will focus on machining parameter and the method used to optimize MRR, EWR and SR. The parameters that would be studied in this project are:

i. Peak current
ii. Pulse off duration
iii. Pulse on duration
iv. Polarity
v. Servo voltage

This project also focuses on the methods used which are GRA, OA and ANOVA in order to obtain the data. All of the methods used in this project were aimed to evaluate the best and optimum parameter stated above. SR, EWR and MRR could simultaneously satisfy requirements of both quality and as well as productivity with special emphasis on reduction of electrode wear that ensures increase in tool life. The optimal setting ensured minimization of SR and EWR, while maximizing MRR.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This section provides the basic fundamentals of the EDM process, parameters and methods involved in this project. A literature review is a body of text that aims to review the critical points of current knowledge and studies related to the project given.

2.2 Electrical discharge machine (EDM)

Electrical discharge machining (EDM) is one of the most extensively used non-conventional material removal processes. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage in the manufacture of mould, die, automotive, aerospace and surgical components. In addition, EDM does not make direct contact between the electrode and the workpiece eliminating mechanical stresses, chatter and vibration problems during machining. Today, an electrode as small as 0.1 mm can be used to construct holes into curved surfaces at steep angles without drill 'wander'. (S. Kalpajian et al., 2003)

S. Webzell, (2001) states that, the foundation of EDM can be traced as far back as 1770, when the English chemist, Joseph Priestly, discovered the erosive effect of electrical discharges or sparks. Nevertheless, it was only in 1943 at the Moscow University where Lazarenko exploited the destructive properties of electrical discharges for constructive use. They developed a controlled process of machining difficult-to-machine metals by vaporizing material from the surface of metal. The Lazarenko EDM system used resistance–capacitance type of power supply, which was commonly used at the EDM machine in the 1950s and later served as the model for successive development in EDM. (A.L. Livshits et al., 1960)

One of the conventional methods to avoid gap contamination is pressure flushing or suction flushing. Nevertheless, it is not always possible to make holes for flushing in electrodes, and even if possible, a uniform flow rate of the dielectric is difficult to obtain over a large working area. The periodical lifting of the electrode is another conventional method but too often lifting lowers the removal rate and the stagnation points at the bottom gap of the electrode cannot be avoided where arcing is apt to occur.

A self-flushing system which is based on a pumping effect by special movement of the electrode was proposed by Masuzawa et al., 1983. Kremer et a1., 1983 reported superior productivity of ultrasonic imposed EDM where ultrasonic vibration helps particles flow out of the gap smoothly.

2.3 Die-sinking EDM

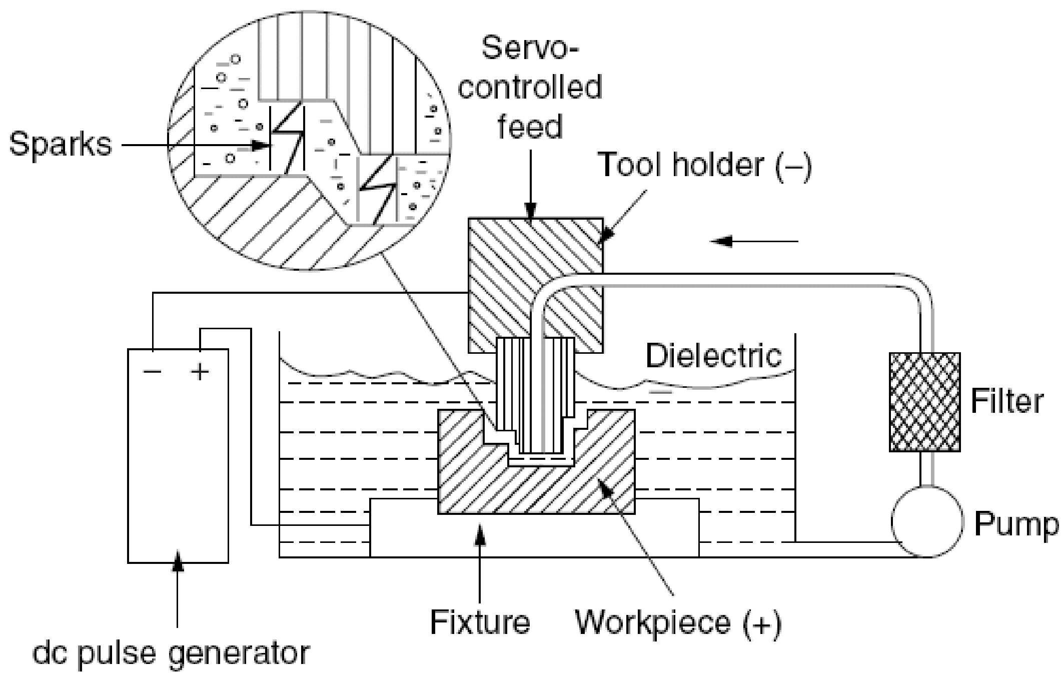

Figure 2.1: Schematic diagram of basic EDM System

Die-sinking EDM machines are also known as ram or vertical EDMs. The equipment used to perform the experiments was a die-sinking EDM machine of type AQ55L (ATC). Also, a jet flushing system in order to assure the adequate flushing of the EDM process debris from the gap zone was employed. The dielectric fluid used for the EDM machine was kerosene. Figure 2.1 shows the schematic diagram of a basic EDM system.

Die-sinking EDM, has four sub-systems, namely:

i. DC power supply to provide the electrical discharges, with controls for voltage, current, duration, duty cycle, frequency, and polarity.
ii. Dielectric system to introduce fluid into the voltage area/discharge zone and flush away work and electrode debris, this fluid is usually a hydrocarbon or silicone based oil.
iii. Consumable electrode.
iv. Servo system to control in-feed of the electrode and provide gap maintenance

2.3.1 Principles of Die-sinking EDM

The workpiece is mounted on the table of the machine tool and the electrode is attached to the ram of the machine. A DC servo unit or hydraulic cylinder moves the ram and electrode in a vertical motion and maintains proper position of the electrode in relation to the workpiece. The positioning is controlled automatically and with extreme accuracy by the servo system and power supply. During normal operation the electrode never touches the workpiece, but is separated by a small spark gap. During operation, the ram moves the electrode toward the workpiece until the space between them is such that the voltage in the gap can ionize the dielectric fluid and allow an electrical discharge or spark to pass from the electrode to the workpiece.

2.3.2 EDM Spark

Kuneida et al., (2005) state, in EDM, the tool (anode) and the work piece (cathode) are immersed in a dielectric medium separated from each other by a small gap of the order of about 5-10 mm. A controlled spark is generated between the two electrodes by applying a voltage (200 V) which breaks down the dielectric medium causing the voltage falls to about 25-30 V (discharge voltage) and the current to rise to a constant value set by the operator. During the on- time of EDM spark (of the order of microseconds), electrons start flowing from cathode to anode which ionizes the dielectric medium and form a plasma channel between the cathode and anode. The intense heat generated in the plasma channel melts and even vaporizes some of the work and tool material causing material removal. DiBitonto DD, Eubank PT, (1989) shows the molten metal is held back at its place due to the large plasma pressure and as soon as the spark on-time is over (the spark collapse) the dielectric gushes back to fill the void. This sudden removal of pressure results in a violent ejection of the molten metal from the work surface forming small craters at locations, where the material has been removed. Controlled spark discharges between the tool and workpiece give the desired material removal and production of the cavities of desired shape on the work surface.

2.3.3 Dielectric Fluid

Kuneida et al. (2005) stated that for EDM, the dielectric serves to concentrate the discharge energy into a channel of very small cross-sectional area. It also cools the two electrodes, and flushes away the products of machining from the gap. The electrical resistance of the dielectric influences the discharge energy and the time of spark initiation. Dielectric fluid acts as an electrical insulator to help control the spark discharges. Thermal processing is required to be carried out in the absence of oxygen so that the process can be controlled and oxidation avoided.

Oxidation often leads to poor surface conductivity of the workpiece hindering further machining. Hence, dielectric fluid should provide an oxygen free machining environment. Moreover, during sparking it should be thermally resistant as well.

Ali Ozgedik et al. (2005) described that the use of kerosene as a dielectric liquid is very common in the published research. Distilled water, water solutions of sugar, glycol, glycerin and polyethylene glycol are also used as dielectric fluids. The use of kerosene gives a higher workpiece removal rate with increasing current compared with the other dielectrics. EWR increases with increasing current for kerosene while it decreases with the other dielectrics. Kerosene dielectric gives lower relative tool wear values compared with the other dielectrics for a low to medium range of current.

The functions of the dielectric fluid are to:

i. Act as an insulator between the tool and the workpiece.
ii. Act as coolant.
iii. Act as a flushing medium for the removal of the chips.

2.4 Material Removal Rate (MRR)

Maximum of MRR is an important indicator of the efficiency and cost effectiveness of the EDM process, however increasing MRR is not always desirable for all applications since this may sacrifice the surface integrity of the workpiece. A rough surface finish is the outcome of fast removal rates.

The material removal rate, MRR in EDM is calculated by the following formula:

$$MRR = \frac{\mathrm{Wb} - \mathrm{Wa}}{\mathrm{T}} \quad (2.1)$$

Where:
W_b = weight of workpiece material before machining (g)
W_a = weight of workpiece material after machining (g)
T = machining times (min)

2.5 Electrode Wear Ratio (EWR)

In EDM, the tool wear problem is very critical since the tool shape degeneration directly affects the final shape of the die cavity. The EDM operations, performed using tools designed and produced by considering the geometric tool wear characteristics, reduce the machining errors to a minimum level and result in parts of higher quality and lower cost.

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

Where:
EWW = weight of electrode used (g)
WRW = weight of workpiece used (g)

Although other ways of measuring MRR and EW do exist, in this work the material removal rate and electrode wear values have been calculated by the weight difference of the sample and electrode before and after undergoing the EDM process.

2.6 Surface Roughness (SR)

The EDM surface is formed by a series of discrete discharges between the electrode and workpiece, and consequently, an inspection of the machined surface reveals the presence of many craters. This machining technique is applicable to a wide variety of conductive materials irrespective of their mechanical properties, e.g. their hardness, strength, or toughness, etc. Furthermore, since no direct contact occurs between the electrode and the workpiece, the EDM process is suitable for the machining of brittle materials such as ceramic, and for those materials which are not readily machined using traditional machining methods.

According to an investigation performed by L.C. Lim (1991), small erosion area (SEA) machining (0.09–0.80 cm2) is one of the most problematic forms of EDM since the integrity of the EDM surface is degraded by the unstable arcing which always occurs during the machining process. The quality of an EDM product is evaluated in terms of its surface integrity, which is characterized by the surface roughness, and by the presence of a white layer, surface cracks, and residual stress. The roughness of the EDM surface is associated with the distribution of the craters formed by the electric sparks. Lim et al., (1991) has reported that only 15% of the molten workpiece material is flushed away by the dielectric. The remaining material re-solidifies on the EDM surface due to the fast cooling rate generated by the dielectric. This recast layer is referred to as the white layer since it is very difficult to etch and because its appearance when observed through an optical microscope is white.

2.7 EDM process parameters

Several parameters requirement should be considered in this EDM process such as servo voltage, peak current, pulse on-duration, pulse off-duration, workpiece polarity and dielectric pressure.

2.7.1 Servo Voltage

Servo voltage in EDM is related to the spark gap and breakdown strength of the dielectric. Before current can flow, the open gap voltage increases until it has created an ionization path through the dielectric. Once the current starts to flow, voltage drops and stabilizes at the working gap level. The preset voltage determines the width of the spark gap between the leading edge of the electrode and workpiece.

The range of voltage available in EDM equipment is between 40 to 400 DC. Higher voltage settings increase the gap, which improve the flushing conditions and help to stabilize the cut. MRR, electrode wear rate (EWR) and surface roughness increases, by increasing open circuit voltage, because electric field strength increases. (Kansal HK, Singh S, Kumar P et al., 2005)

2.7.2 Peak Current

The current increases until it reaches a preset level during each pulse on-time, which is known as peak current. Peak current is governed by surface area of cut. Higher peak current is applied during roughing operation and details with large surface area. This is the most important parameter because the machined cavity is a replica of tool electrode and excessive wear will hamper the accuracy of machining. New improved electrode materials like graphite, can work on high currents without much damage. (Ho KH, Newman ST et al., 2003)

2.7.3 Pulse On and Off Duration

In the study, Kansal HK, Singh S, Kumar P et al., (2005) state that, pulse duration is commonly referred to as pulse on-time and pulse interval is called pulse off-time. These are expressed in units of microseconds. Since all the work is done during pulse duration, hence this parameter and the number of cycles per second (frequency) are important. Material removal rate (MRR) depends upon the amount of energy applied during the pulse duration. Increased pulse duration also allows more heat to sink into the workpiece and spread, which means the recast layer will be larger and the heat-affected zone will be deeper. Material removal rate tends to decrease after an optimal value of pulse duration.

Pulse interval mainly affects machining speed and stability of cut. Shorter interval results in faster machining operation. However, if the interval is too short, the ejected workpiece material will not be flushed away with the flow of the dielectric fluid and the dielectric fluid will not be deionized. This results in instability of the next spark. Erratic cycling due to unstable spark results in prolonged machining time. At the same time, pulse interval must be greater than the deionization time to prevent continued sparking at one point. Fuller JE (1996)

2.7.4 Workpiece Polarity

The negative polarity of the tool − polarity gives a lower tool wear than that of + polarity in the range of low to medium discharge current values. At high current settings, the polarity has no significant effect on tool wear. A slight decrease relative wear is observed with increasing current in − polarity. In the case of + polarity, relative wear decreases significantly with increasing current. Relative wear does not vary significantly with current at high settings of current for both polarities. (Lee SH, Li XP et al., 2001)

It is very important to pay attention to the recommended polarity of various electrode-work piece combinations. The wrong polarity can have significant implications on speed, wear, and stability. It is best to consult the specific power supply technology documentation for polarity recommendations. General polarity guidelines are listed in Table 2.1.

Table 2.1: General polarity guidelines

Electrode Material	**Polarity**
Graphite on Steel: general purpose and low wear	Electrode Positive
Graphite on Steel: high speed and 20% wear	Electrode Negative
Graphite on Copper	Electrode Negative
Copper on Steel	Electrode Positive
Copper Tungsten on Steel	Electrode Positive
Copper Tungsten on Carbide	Electrode Negative

2.7.5 Dielectric Pressure.

Cogun C et al. (2002) write in their study that, the machining condition turns into an unstable regime when there is no flushing. This condition is called the “static dielectric condition” or “static condition”. Tool wear increases rapidly when the flushing pressure is increased beginning from the static condition. Increasing dielectric pressure at high-pressure settings does not result in a significant increase in tool wear. The increase in dielectric pressure at low-pressure settings results in a significant increase in relative wear, whereas the increase in pressure at high dielectric pressure settings insignificantly affects relative wear.

2.8 Grey Relational Analysis (GRA)

The Grey theory can provide a solution of a system in which the model is unsure or the information is incomplete. It also provides an efficient solution to the uncertainty, multi-input and discrete data problem. The relation between machining parameters and performance can be found out with the Grey relational analysis. (J.L. Deng et al., 1989)

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will describe about the overall process of methodology in this project, from the beginning until end of the project. There are four main processes that start with experimental, collecting the data, result analysis and confirmation test. All the processes will be described in this chapter by the flow chart. During this part, every information and data will be gathered together and concluded according to the objectives and scope of the project.

3.2 Flow Chart

Flow chart is an important step in order to make sure the project can be done on time. Based from the flow chart, the project started with the literature review of the project. Research was made through journals, websites, books and other related sources based on the title given. The flow chart for this project is shown as in Figure 3.1.

The design of experiment is conducted after all the information about the project is gathered. The required parameters need to be defined as a design factor. The experiment start after workpiece, electrode and machine setup was prepared. Then, collect the data of the experiment and analyse it based on the constructed table attached in the appendices.

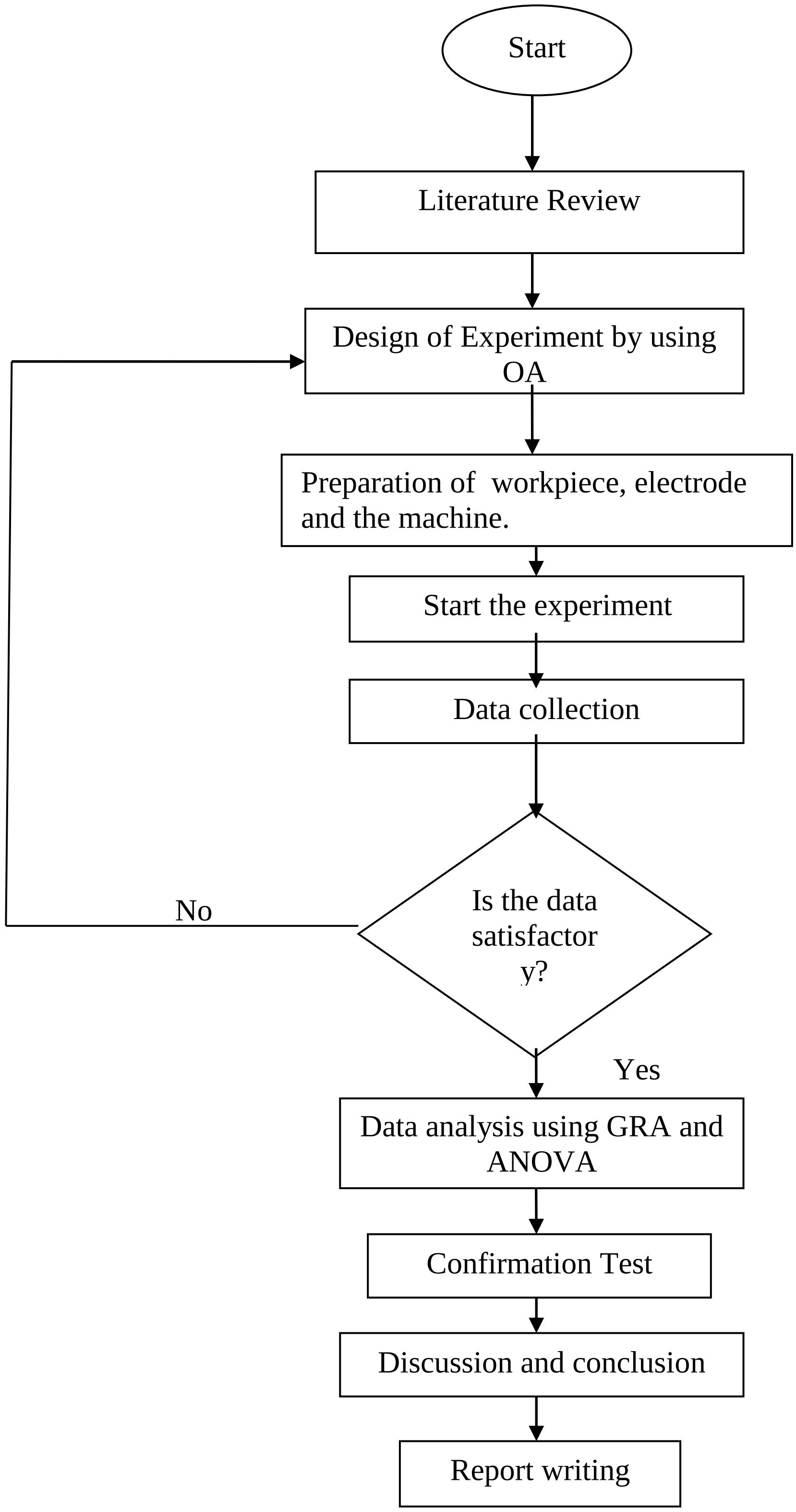

Figure 3.1: Flow chart outlining the steps undertaken.

3.3 Experimental Setup

3.3.1 Electrode Material

The electrode material used in this experiment is Copper Tungsten (CW75). The estimated size of the electrode used is 5 mm in diameter and 6.5 mm in length. The properties of the copper are listed in Table 3.1.

Table 3.1: Copper Tungsten properties.

Work Materials: Copper Tungsten 75% Tungsten 25% Copper	
Density	15.2 g·cm^{-3}
Hardness	HB 200
Melting point (^{0}C)	3500
Electrical resistivity (μΩ cm)	5.5

Source: S.H, Lee, X.P. Li (2001)

3.3.2 Workpiece Material

The workpiece used in this project is titanium which is a conductive material. Titanium is recognized for its high strength-to-weight ratio. It is a strong metal with low density that is quite ductile (especially in an oxygen-free environment), lustrous, and metallic-white in colour. The estimated size of the workpiece is 25 mm in diameter and 6 mm in height. Table 3.2 shows the properties.

Table 3.2: Titanium properties.

Work Materials: Titanium	
Density	4.506 g·cm^{-3}
Hardness (Brinell hardness)	716 MPa
Young's modulus	116 GPa
Thermal expansion (25 °C)	8.6 µm·m^{-1}·K^{-1}
Molar heat capacity	25.060 J·mol^{-1}·K^{-1}
Thermal conductivity	21.9 W·m^{-1}·K^{-1}

Source: Lide, D. R., et al (2005)

3.3.3 Machine

The machine used in this study is an AQ55L (ATC) Die-sinking EDM. The picture of the Die-sinking EDM is shown in Figure 3.2.

Figure 3.2: AQ55L (ATC) Die-sinking EDM.

3.4 Design of Experiment

In identifying the effect of machining parameters in EDM, the Design of Experiment (DOE) is used to the extent possible. The application of DOE requires careful planning and expert analysis of results. In the grey relational analysis, the experimental results of electrode wear ratio, material removal rate and surface roughness are first normalized in the range between zero and one, which is also called the grey relational generating. Next, the grey relational coefficient is calculated from the normalized experimental results to express the relationship between the desired and actual experimental results. Then, the grey relational grade is computed by averaging the grey relational coefficient corresponding to each performance characteristic (J.L. Lin et al., 2001).

The overall evaluation of the multiple performance characteristics is based on the grey relational grade. As a result, optimization of the complicated multiple performance characteristics can be converted into optimization of a single grey relational grade. Optimal level of the process parameters is the level with the highest grey relational grade. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. With the grey relational analysis and statistical analysis of variance, the optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the process parameter design (J.L. Lin et al., 2001).

3.4.1 Design Factor

There are a large number of factors to consider within the EDM process, but in this work the level of the pulse-off time, pulse-on duration, peak current, workpiece polarity, servo voltage and dielectric flushing pressure have only been taken into account as design factors. The reason why these six factors have been selected as design factors is that they are the most widespread and used amongst EDM researchers. Besides that, the level of experimentation in this project is three which are low, medium and high

Table 3.3: Machining parameters and their respective levels

Factors	**Description**	**Level 1**	**Level 2**	**Level 3**	**Units**
A	Polarity, *P*	Workpiece(+) Tool (-)	Workpiece(-) Tool (+)	-	Positive (+) Negative(-)
B	Peak Current (A)	2	16	30	Ampere
C	Pulse-on-duration, τ_{on}	10	205	400	microsec
D	Pulse-off-duration, τ_{off}	50	175	300	microsec
E	Servo Voltage	40	70	90	V

Reference: M. M. Rahman, Md. Ashikur Rahman Khan, K. Kadirgama M. M. Noor and Rosli A. Bakar (2010) Modeling of Material Removal on Machining of Ti-6Al-4V through EDM using Copper Tungsten Electrode and Positive Polarity

3.4.2 Experimental Design

Table 3.3 shows the machining parameters and their respective levels based on literature reviews conducted. Six factors are selected with a combination of four electrical parameters and two non-electrical parameters. All the parameters were selected for the control factors because they affected MRR, EWR and SR analysis. The values at various levels were referred from the manual of EDM.

Based on OA method of DOE, an L_{18} (2^1 x 3^4) orthogonal arrays table with 18 rows (number of experiments), was selected for the experimentation (Nicolo Belavendram, 2005). Experimental layout of L_{18} orthogonal array is shown in Appendix B2.

L_{18} (2^1 x 3^4) orthogonal array has a special property where two degrees of freedom are taken up between a 2-level and 3-level factor. In general, the experimenter should seek the smallest orthogonal array for an experiment.

The use of the orthogonal array with the grey relational analysis to optimize the process includes the following steps (J.L. Lin et al., 2001):

i. Select the appropriate orthogonal array and assign the process parameters to the orthogonal array.
ii. Conduct the experiments based on the arrangement of the orthogonal array.
iii. Normalize the experimental results of electrode wear ratio, material removal rate and surface roughness.
iv. Perform the grey relational generating and calculate the grey relational coefficient.
v. Calculate the grey relational grade by averaging the grey relational coefficient.
vi. Analyze the experimental results using the grey relational grade and statistical analysis of variance.
vii. Select the optimal levels of process parameters.
viii. Verify the optimal process parameters through the confirmation experiment.

The normalized experimental results for MRR which observes the higher the value, the better performance criteria. Meanwhile, EWR and SR observe the lower-the-better performance criteria. Larger normalized results correspond to the better performance and the best normalized result should be equal to 1.The normalized values are ranged between zero and one. The larger values yield better performance and the ideal value should be equal to one (M.A.Azmir et al., 2008).

Next, the Grey relational coefficient is calculated to express the relationship between the ideal and actual normalized experimental results. The grey relational grades are calculated by averaging GRCs for each performance characteristic. The higher the GRG represents that the experimental result is closer to the ideally normalized value (M.A.Azmir et al, 2008).

3.5 Analysis of Variance (ANOVA)

The purpose of the Analysis of Variance (ANOVA) is to investigate which machining parameters significantly affect the performance characteristic. In this study, the STATISTICA software was used to construct ANOVA table.

3.6 Confirmation Experiment

The confirmation tests were conducted by selecting the optimum combinations of machining factors. These confirmation tests were used to predict and verify the improvement in the quality characteristics for machining of Titanium with respect to the chosen initial parameters setting.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, the analysis of the project will be explained. The effect of selected parameter, workpiece polarity, pulse-off time, pulse-on time, peak current, and servo voltage will be shown by using grey relational analysis (GRA). Statistical analysis way also performed to determine the significance of each parameter. Full results of the experiment and analysis will show in this chapter.

4.2 Orthogonal Array Experiment

Orthogonal arrays for the parameter design indicating the number of and conditions for each experiment. The selection of orthogonal arrays is based on the number of parameters and the levels of variation for each parameter that have been determined.

In this study, five (5) parameters were selected, one (1) that has two (2) levels of machining and the other four (4) have three (3) levels of machining parameter. They are shown in Table 4.1. Based on parameter and level of parameter, L18 orthogonal array is selected. Therefore, 18 experiment need to be conducted in this study. The experiment result is shown in Table 4.2.

Table 4.1: Parameter and its level

Factors	Description	Level 1	Level 2	Level 3	Units
A	Polarity, *P*	Workpiece(+) Tool (-)	Workpiece(-) Tool (+)	-	Positive (+) Negative(-)
B	Peak Current (A)	2	16	30	Ampere
C	Pulse-on-duration, τ_{on}	10	205	400	microsec
D	Pulse-off-duration, τ_{off}	50	175	300	microsec
E	Servo Voltage	40	70	90	V

Reference: M. M. Rahman, Md. Ashikur Rahman Khan, K. Kadirgama M. M. Noor and Rosli A. Bakar (2010) Modeling of Material Removal on Machining of Ti-6Al-4V through EDM using Copper Tungsten Electrode and Positive Polarity

Table 4.2: Results of MRR, EWR and SR in L_{18} OA

Exp	**A**	**B**	**C**	**D**	**E**	**Average values for**		
						MRR (g/min)	**EWR (%)**	**SR (µm)**
1	+	02	010	050	40	0.000477	143.7063	1.262
2	+	02	205	175	70	0.000240	13.4571	1.573
3	+	02	400	300	90	0.000024	90.1408	1.284
4	+	16	010	050	70	0.001805	22.9917	2.470
5	+	16	205	175	90	0.000470	29.7872	2.953
6	+	16	400	300	40	0.002165	35.1039	2.358
7	+	30	010	175	40	0.000687	25.9709	3.215
8	+	30	205	300	70	0.001437	3.7123	2.956
9	+	30	400	050	90	0.001377	15.9806	2.590
10	-	02	010	300	90	0.000001	297.222	1.115
11	-	02	205	050	40	0.000280	51.6129	1.783
12	-	02	400	175	70	0.000124	39.9463	1.934
13	-	16	010	175	90	0.001237	14.0162	2.462
14	-	16	205	300	40	0.001253	34.0426	2.859
15	-	16	400	050	70	0.001557	34.9036	2.823
16	-	30	010	300	70	0.000933	12.8571	3.059
17	-	30	205	175	90	0.000710	14.5540	3.066
18	-	30	400	050	40	0.001091	13.8493	2.956

4.3 Grey relational analysis for the experimental results

In the grey relational analysis, data pre-processing is first performed in order to normalize the raw data for analysis. MRR is '*the bigger-the-better'* performance criteria while EWR and SR are '*the lower-the-better*' performance response. If the target value of the original sequence is '*the bigger-the-better'*, it can be calculated as follows:

$$x_{ij} = \frac{y_{ij} - \min_i y_{ij}}{\max_i y_{ij} - \min_i y_{ij}} \tag{4.1}$$

Where y_{ij} is the i th experimental results in the j th experiment.

Meanwhile, for target value which is '*the lower-the-better*', then the original sequence is normalized as follows:

$$x_{ij} = \frac{\min\limits_{i} y_{ij} - y_{ij}}{\max\limits_{i} y_{ij} - \min\limits_{i} y_{ij}} \tag{4.2}$$

Table 4.3 shows the normalized results for MRR, EWR and SR.

Table 4.3: Normalized results

Exp	**Normalized Values**		
	MRR(g/min)	**EWR(%)**	**SR(µm)**
1	0.778651	0.521195	0.930000
2	0.889556	0.966799	0.781905
3	0.989372	0.705534	0.919524
4	0.166359	0.934414	0.354762
5	0.783272	0.911162	0.124762
6	0.000000	0.927118	0.408095
7	0.682994	0.924164	0.000000
8	0.336414	1.000000	0.123333
9	0.364140	0.958201	0.297619
10	1.000000	0.000000	1.000000
11	0.871072	0.836801	0.681905
12	0.943161	0.876549	0.610000
13	0.428835	0.964894	0.358571
14	0.421442	0.896630	0.169524
15	0.280961	0.893730	0.186667
16	0.569316	0.963062	0.074286
17	0.672366	0.963062	0.070952
18	0.496303	0.965463	0.122857

Next, the Grey relational coefficient is calculated to express the relationship between the ideal and actual normalized experimental results. The grey relational coefficient can be calculated as shown in Equation 5.

$$\xi_{ij} = \frac{\min_i \min_j \left| x_i^o - x_{ij} \right| + \zeta \max_i \max_j \left| x_i^o - x_{ij} \right|}{\left| x_i^o - x_{ij} \right| + \zeta \max_i \max_j \left| x_i^o - x_{ij} \right|} \tag{4.3}$$

Where x_i^0 is the ideal normalized result for the i th performance characteristics. The calculation for the deviation sequences shown in Appendix B2. ζ is the distinguishing coefficient which is set between zero and one and in this study it was set to $\zeta = 0.9$.

Then the grey relational grade is computed by averaging the grey relational coefficient corresponding to each performance characteristic. The overall evaluation of the multiple performance characteristics is based on the grey relational grade. Table 4.4 shows grey relational coefficient, GRCs and grey relational grade, GRGs.

Table 4.4: GRCs and GRGs

Exp	Grey Relational Coefficients			Grey Relational Grade
	MRR (g/min)	EWR (%)	SR (µm)	
1	0.8026	0.6527	0.9278	0.7944
2	0.8907	0.9644	0.8049	0.8867
3	0.9883	0.7535	0.9179	0.8866
4	0.5191	0.9321	0.5824	0.6779
5	0.8059	0.9102	0.5070	0.7410
6	0.4737	0.9251	0.6033	0.6674
7	0.7395	0.9199	0.4737	0.7110
8	0.5756	1.0000	0.5066	0.6941
9	0.5860	0.9556	0.5617	0.7011
10	1.0000	0.4737	1.0000	0.8246
11	0.8747	0.8465	0.7389	0.8200
12	0.9406	0.8794	0.6977	0.8392
13	0.6118	0.9625	0.5839	0.7194
14	0.6086	0.8970	0.5201	0.6752
15	0.5559	0.8944	0.5253	0.6589
16	0.6763	0.9665	0.4930	0.7119
17	0.7331	0.9606	0.4921	0.7286
18	0.6412	0.9630	0.5068	0.7037

The higher grey relational grade represents that the corresponding experimental result is closer to the ideally normalized value. Experiment 2 has the best multiple performance characteristics among 18 experiments because it has the highest grey relational grade shown in Table 4.4. Optimization of the complicated multiple performance characteristics can be converted into optimization of a single grey relational grade.

The Response Table is constructing here to calculate the average grey relational grade for each cutting parameter level. It is done by sorting the grey relational grades corresponding to levels of the cutting parameter in each column of the orthogonal array, and taking the average of the same level.

For example, the mean of the grey relational grade for the workpiece polarity at levels 1 and 2 can be calculated by averaging the grey relational grade for the experiments 1 to 9 and 10 to 18, respectively (Table 4.4). Using the same method, calculations are performed for each cutting parameter level and the response table is constructed as shown in Table 4.5.

Table 4.5: Response table for the grey relational grade

Symbol	**Parameter**	**Grey Relational Grade**			**Max-Min**
		Level 1	**Level 2**	**Level 3**	
A	Polarity *P*	0.7511	0.7424	-	0.0087
B	Peak Current (A)	0.8419	0.6900	0.7084	0.1519
C	Pulse on time τ_{on}	0.7399	0.7576	0.7424	0.0148
D	Pulse off time τ_{off}	0.7302	0.7668	0.7433	0.0366
E	Servo voltage V	0.7286	0.7448	0.7669	0.0383
Total Mean Value of the Grey Relational Grade= 0.7468					

Meanwhile, the total mean of the grey relational grade for the 18 experiments is also calculated and listed in Table 4.5. Figure 4.1 shows the grey relational grade graph. Basically, the larger the grey relational grade, the better is the performance characteristics. However, the relativity among the machining parameters for the multiple performance characteristics still needs to be known so that the optimal combinations of the machining parameter levels can be determined more accurately.

Based on Table 4.5, the optimal machining parameter setting is A1B1C2D2E3 or maintaining polarity at level 1 (workpiece (+)), peak current at level 1 (2A), pulse on duration at level 2 (205µs),pulse off duration at level 2 (175µs) and servo voltage at level 3(90V).

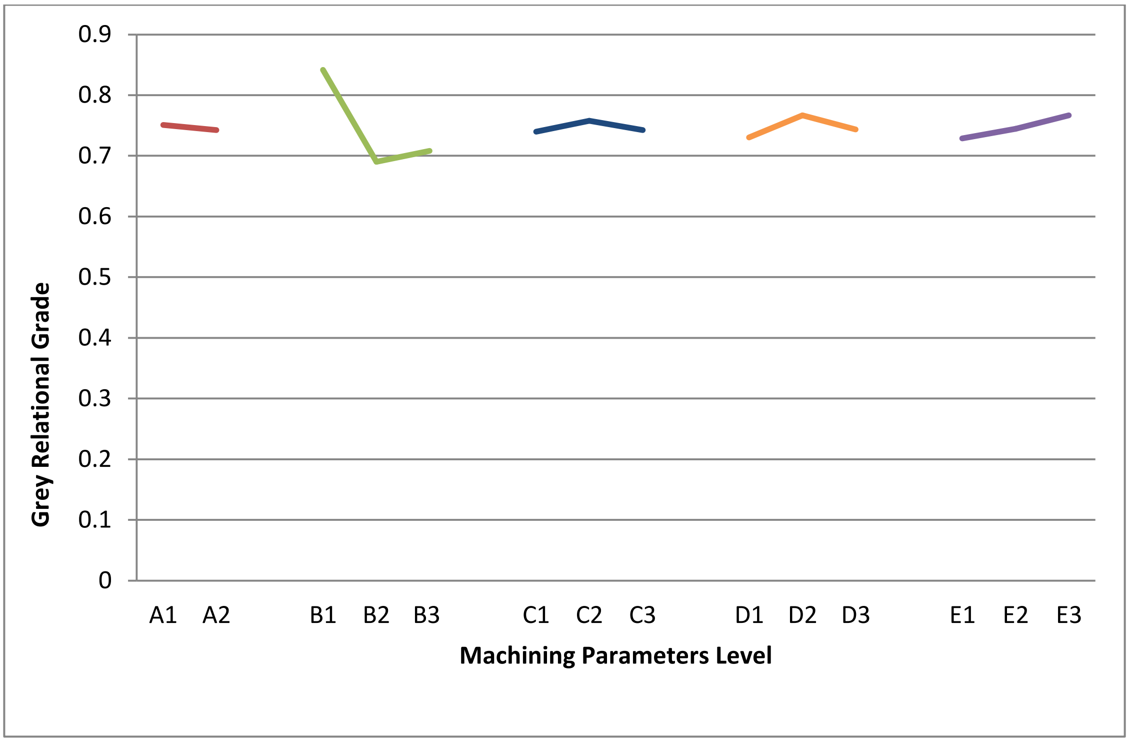

Figure 4.1: Grey relational grade plot.

4.4 Analysis of Variance (ANOVA)

The Analysis of Variance (ANOVA) table presents another way of testing the effects for significance. The general concept of analysis of variance is based on the partitioning of the sums of squares (SS) for total variation of response into sums of squares for individual effects and residual variation (error).

The purpose of the Analysis of Variance (ANOVA) is to investigate which machining parameters significantly affect the performance characteristic. Using STATISTICA software, the ANOVA is performed and the results of ANOVA for Grey relational grade values with multiple performance characteristics are shown in Table 4.6. The percentage contribution by each of the machining parameter can be used to evaluate the importance of the machining parameter change on the performance characteristic.

The Fisher's *F* test can also be used to determine which machining parameters have a significant effect on the performance characteristic. Usually, when *F* is large, it shows that the change of the machining parameter has a significant effect on the performance characteristic. Results in Table 4.6 shows that the peak current is the most significant parameter with 86.3321% contribution for affecting the multi-response characteristics and the *F* value larger than others parameter.

Table 4.6: Results of the analysis of variance

Symbol	Parameter	D.O.F	SS	MS	F	Contribution (%)
A	Polarity,*P*	1	0.000344	0.000344	0.65154	0.3599
B	Peak Current,A	2	0.082511	0.041255	78.1164	86.3321
C	Pulse-on time τ_{on}	2	0.000453	0.000226	0.42864	0.474
D	Pulse-off time τ_{off}	2	0.002983	0.001491	2.82367	3.1211
E	Servo voltage,V	2	0.001888	0.000944	1.78736	1.9754
	Error	8	0.004225	0.000528		4.4207
	Total	17	0.095574			

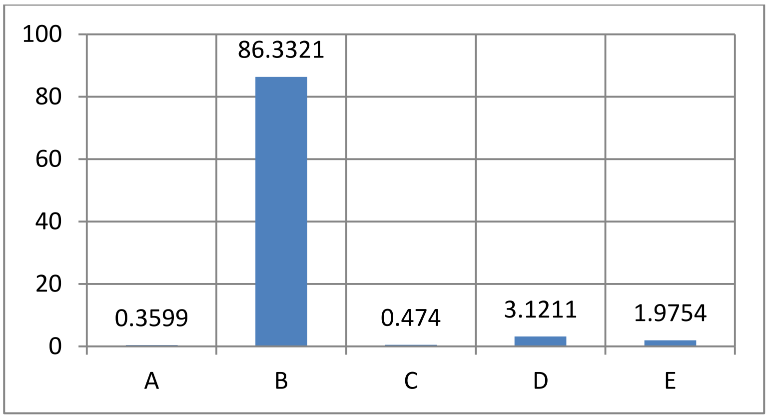

Figure 4.2: Percentage contribution vs Parameters

From the Figure 4.2, the highest percentage contribution was parameter B with the value of 86.3% and the lowest percentage contribution was parameter A with 0.4%. Higher percentage contribution determine the most significant parameter to the product.

4.5 Confirmation Test

Once the optimal level of the machining parameters is selected, the final step is to predict and verify the improvement of the performance characteristic for machining Titanium Alloy Ti-6Al-4V utilizing Copper Tungsten as electrode using the optimal level of the machining parameters. The estimated grey relational grade $\gamma^{\wedge}$ using the optimal level of the machining parameters can be calculated as shown in Equation 6:

$$\gamma^{\wedge} = \gamma_m + \sum_{i=1}^{q}(\gamma_i - \gamma_m) \quad (6)$$

Where γ_m the total mean of the Grey relational grade is, γ_i is the mean of the Grey relational grade at optimal level and q is the number of the machining parameters.

Table 4.7 shows the result of the confirmation experiment using their respective optimal cutting parameters. MRR increased to 0.000361 g/min, EWR is greatly reduced from 14.5% to 11.1% and SR is improved from 1.573 to 1.371 μm. The improvement in grey relational grade is 0.0124. It is clearly shown that the multiple performance characteristics in the EDM process are greatly improved through this study.

Table 4.7: Result of the confirmation experiment A2B2C1D2E1F3

	Initial cutting parameters	Optimal cutting parameters	
		Predicted	Experimental
Setting level	A1B1C2D2E2	A1B1C2D2E3	
MRR (g/min)	0.000240		0.000361
EWR (%)	13.5		11.1
SR (μm)	1.573		1.371
GRG	0.8867		0.8991
Improvement of GRG = 0.0124			

4.6 Most Significant Factor- Peak Current (B)

Peak current is the amount of power used in discharge machining, measured in units of amperage, and is the most important machining parameter in EDM. During each on-time pulse, the current increases until it reaches a preset level, which is expressed as the peak current. Based on the result of the Figure 4.2, the most significant factor is peak current.

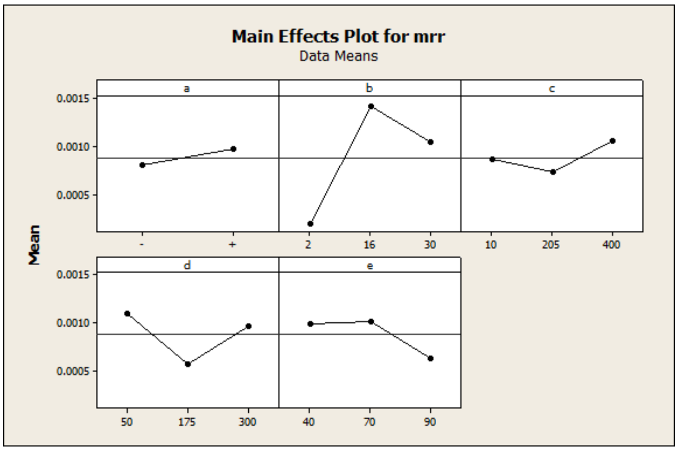

Figure 4.3: MRR plot

The Figure 4.3, its clearly shows that with increasing peak current, the material removal rate (MRR) will also increase. This is because, when increasing peak current, the potential different between the electrode with the workpiece will also increase, also, as the peak current increase, the intensity of the current also will increase, the factor of intensity is the one which most affects the MRR variable, so that when it increases, the value of material removal rate also tends to increase. This tendency coincides exactly with what would be expected a priori, based on the experience acquired with other types of materials. (I. Puertas, 2004).

The higher the material removal rate in the EDM process, the better is the machining performance. However increasing MRR is not always desirable for all applications since this may scarify the surface integrity of the workpiece. Other than that, higher current will shorten the machining time but it also will produce rough surface. Thus, optimum peak current are required in order to maximize MRR while minimize EWR and SR respectively.

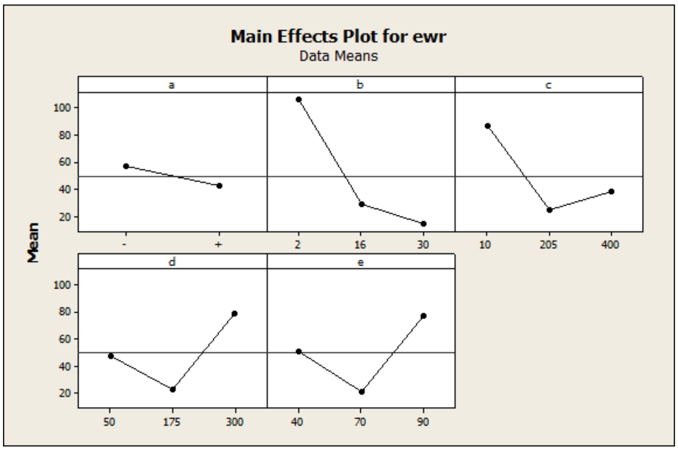

Figure 4.4: EWR plot

Peak current also will affects the electrode wear ratio (EWR) of the electrode. he Figure 4.4, shows that electrode wear ratio is varies with the different peak current. Electrode wear is depending on the electrode materials and energy of the discharge. The higher the melting temperatures of the studied materials, the lower are the electrode wear. (S.H. Lee, 2001).

As the peak current increases, the intensity of the current also will increase. The most influential factor over EW is intensity, in such a way that the value of the wear decreases greatly when intensity is increased, at least down to a minimum value after which the value of EW begins to grow. This tendency is what would be expected, a priori, as higher values for the intensity factor usually lead to lower values of electrode wear. (I. Puertas, 2004).

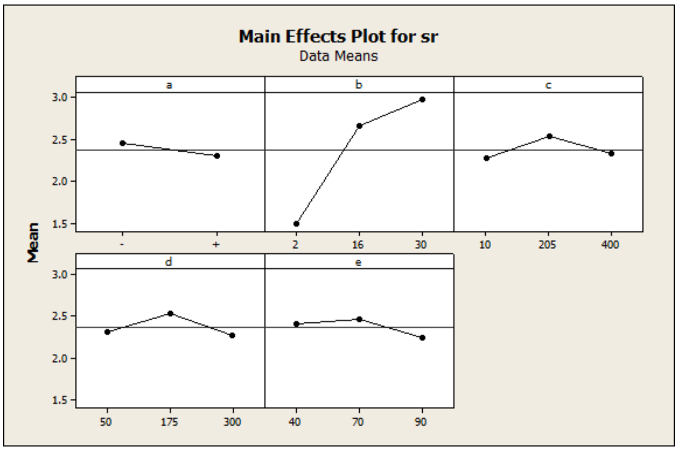

Figure 4.5: SR plot

The surface roughness of an EDM product can be defined as a chip-forming process where the chips are spherical debris melted by sparks. So the surface roughness is depending on the size of spark crater. Figure 4.5 shows that the effect of the peak current on the surface roughness (SR). It's clearly show that, as the peak current increase, the value for SR also will increase.

The surface roughness is getting worse with current for all electrode materials. A large discharging energy causes violent sparks and impulsive forces and results in a deeper and larger erosion crater on the surface. Accompanying the cooling process after the spilling molten metal, residues are remaining at the periphery of the crater to form a rough surface. At the lower pulse currents, the surface craters are shallow with larger diameter, and so, the workpiece surface roughness is better. (Ahmet Hascalık, 2007).

4.7 Significant Factor- Pulse-off Time (D)

The second most significant factor was a pulse-off time. Based on Figure 4.2, pulse-off gives 3.12% distribution of the machining parameter. Pulse-off is the amount of time the current is off after making a single crater or pit to the workpiece.

From Figure 4.3, material removal rate (MRR) will decrease with the increasing time but, after reaching at certain time, it will start increase again. As for duty cycle, the MRR response variable also tends to increase when this factor is increased, within the considered work interval. This agrees with the tendency which would be expected a priori, as in general, when pause time tends to decrease whilst pulse time remains constant, which is equivalent in this case to increasing the value of duty cycle material removal rate tends to increase. (I. Puertas, 2004).

Finally, about its performance versus pulse time, material removal rate tends to decrease as pulse time is increased. This behaviour does not fit in entirely with what might have been expected at first as, generally, when the pulse time factor increases, the MRR parameter usually increases up to a maximum value after which it starts to decrease.

From Figure 4.4, electrode wear ratio (EWR) will decrease as the pulse-off time increase, but after its reach certain time, the EWR will start increase. The decreasing EWR as pulse-off increase is due to the lesser contact between the electrode and workpiece so that the wear will also decrease.

In principle, the materials best suited have a very high melting point and a low resistance to electricity. The effect of EDM parameters on electrode wear is seen in Figure4.3; it seems that the trend of wear ratio is increasing with the pulse current. Electrode wear is depending on the electrode materials and energy of the discharge. (Ahmet Hascalık, 2007) But if less time for the electrode has its energy discharge, the wear also will be decrease.

From Figure 4.5, the surface roughness (SR) of the product will be decreased to its minimum after it reaches its maximum with the increasing pulse off. Surface roughness of the product related the micro structure of the product during the machining process. The micro-cracks at surface finish of the process will make the SR increase. The micro-cracks were associated with the development of thermal stresses exceeding the ultimate tensile strength of the material. The primary causes of the thermal stress in the machined surface were the drastic heating and cooling rates and the non-uniform temperature distribution. (B. Ekmekci, 2006).

If the discharge current is too high, long pulse-off time increases the SR. This is due to the fact that the pulse off time must be sufficiently long to acquire a uniform erosion of the material from the surface of the workpiece and stable machining process otherwise a non-uniform erosion of the workpiece surface occurs. Another reason is that the long pulse-off time furnishes good cooling effect and enough time for flush away the molten material and debris from the gap between the electrode and workpiece. Thus, long pulse-off time present fine surface of the workpiece and the same effect is achieved by: K.L. Wu, (2009).

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

For this study, the usage of grey relation analysis for optimizing EDM machining process with multiple objective optimization on the material removal rate (MRR), electrode wear ratio (EWR) and surface roughness (SR) will be concluded in this chapter. Roughly, the result indicates that performance characteristic of EDM process improve using the method that have been proposed in this study.

5.2 Conclusion

For the main conclusions that obtain during the study are as follow:

i. From multiple machining parameter, MRR, EWR and SR it can convert to single parameter by using GRA method.
ii. Based on the result obtain, peak current gives the most significant factor that will affect the MRR, EWR and SR of the process.
iii. Although increasing peak current can increase the MRR but it's also effect EWR and SR during the process, so it's not always desirable for all machining process since it may sacrifice the SR.
iv. ANOVA is very useful to determine the most significant parameter that will affect the process performance characteristic when there are many parameters involved.

5.3 Recommendations

i. There are various statistic software available for use in this study to calculate ANOVA approach such as, STATISTICA, MINITAB, and MICROSOFT EXCELL rather than calculating manually that will take time to finish and not efficient while doing the project.

ii. For future study, by comparing of optimization with other type of advance Taguchi method such as Grey Relation Analysis and Response Surface Method could be made to optimize performance characteristic on MRR, EWR and SR.

iii. For future research, vary the material for the work piece or electrode; because different material will give difference optimize machining parameter.

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APPENDIX A1

APPENDIX A1

Gant Chart for Final Year Project 1

TASK	WEEK													
	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
Identify Title														
Literature review														
Introduction, Define Problem Statement, Project Objective, Project scopes														
Methodology, Plan the experiment, Design the experiment														
Proposal Writing														
Preparation for Presentation														
PSM 1 Presentation														
TASK	WEEK													

APPENDIX A2

Gant Chart for Final Year Project 2

TASK	WEEK														
	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15
Literature Study															
Running Experiment															
Collect the data															
Analysis of data															
Report Writing															
Prepare Presentation															
PSM 2 Presentation															
Report Submission															

APPENDIX B1

APPENDIX B1

Result of the experiment on the workpiece

Experiment number	Work Piece	Before (g)	After (g)	Result (g)
1	2	14.4012	14.3726	0.0286
2	3	14.1429	14.0998	0.0431
3	5	14.4053	14.3982	0.0071
4	6	14.4126	14.3765	0.0361
5	7	12.9299	12.8923	0.0376
6	8	14.1646	14.1213	0.0433
7	9	14.1197	14.0785	0.0412
8	10	13.6274	13.5843	0.0431
9	11	14.1899	14.1486	0.0413
10	12	14.3519	14.3483	0.0036
11	13	12.8639	12.8329	0.0310
12	14	12.9361	12.8988	0.0373
13	15	14.1208	14.0837	0.0371
14	16	14.3840	14.3464	0.0376
15	17	14.2060	14.1593	0.0467
16	18	14.4435	14.4015	0.0420
17	19	12.8538	12.8112	0.0426
18	20	14.1104	14.0613	0.0491

Result of the experiment on the electrode

Experiment number	Before (g)	After (g)	Result (g)
1	7.4027	7.3616	0.0411
2	6.4913	6.4855	0.0058
3	7.5819	7.5755	0.0064
4	7.1151	7.1068	0.0083
5	6.9592	6.9480	0.0112
6	7.1089	7.0937	0.0152
7	7.3093	7.2986	0.0107
8	7.5233	7.5217	0.0016
9	7.1644	7.1578	0.0066
10	7.3616	7.3509	0.0107
11	6.4855	6.4695	0.0160
12	7.5755	7.5606	0.0149
13	7.1068	7.1016	0.0052
14	6.9480	6.9352	0.0128
15	7.0937	7.0774	0.0163
16	7.2986	7.2932	0.0054
17	7.5217	7.5155	0.0062
18	7.1578	7.1510	0.0068

APPENDIX B2

Experimental layout of L_{18} orthogonal array

Surface waviness in L_{18} OA

Exp	*A*	*B*	*C*	*D*	*E*	Average values for		
						MRR (g/min)	EWR (%)	SR (μm)
1	+							
2	+							
3	+							
4	+							
5	+							
6	+							
7	+							
8	+							
9	+							
10	-							
11	-							
12	-							
13	-							
14	-							
15	-							
16	-							
17	-							
18	-							

APPENDIX B3

CALCULATION FOR DEVIATION SEQUENCES | $x_i^0 - x_{ij}$ | IN EQUATION 5

where $x_i^0 = 1$ is the ideal normalized result for the *i* th performance characteristics while x_{ij} is normalized value.

Deviation Sequences	MRR	EWR	SR
No. 1, i=1	0.221349	0.478805	0.070000
No. 2, i=2	0.110444	0.033201	0.218095
No. 3, i=3	0.010628	0.294466	0.080476
No. 4, i=4	0.833641	0.065586	0.645238
No. 5, i=5	0.216728	0.088838	0.875238
No. 6, i=6	1	0.072882	0.591905
No. 7, i=7	0.317006	0.075836	1
No. 8, i=8	0.663586	0	0.876667
No. 9, i=9	0.635860	0.041799	0.702381
No. 10, i=10	0	1	0
No. 11, i=11	0.128928	0.163199	0.318095
No. 12, i=12	0.056839	0.123451	0.390000
No. 13, i=13	0.571165	0.035106	0.641429
No. 14, i=14	0.578558	0.103337	0.830476
No. 15, i=15	0.719039	0.106270	0.813333
No. 16, i=16	0.430684	0.031157	0.925714
No. 17, i=17	0.327634	0.036938	0.929048
No. 18, i=18	0.503697	0.034537	0.877143