

# **Faculty of Manufacturing Engineering**



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Master of Science in Manufacturing Engineering

# PARAMETER OPTIMIZATION ON HYBRID MICRO WIRE ELECTRICAL DISCHARGE TURNING

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#### DECLARATION

I declare that this thesis entitled "Parameter Optimization on Hybrid Micro Wire Electrical Discharge Turning" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



#### APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Manufacturing Engineering.



#### DEDICATION

This thesis is dedicated to

my beloved and great parents, who never stop giving of themselves in countless ways,

my beloved brother and sisters, who stands by me when things look bleak and hope this thesis may inspire you to excel in any field in which you venture during your life journey



#### ABSTRACT

Micro-machining is expected to play an important role in today's manufacturing technology. However, the traditional down-scaling process creates challenges relating to process stability and materials behaviour especially for small difficult-to-machine made materials. Therefore, a suitable material removal process to perform micro-machining on cylindrical components is spark erosion process. In this study, the new hybrid micro-machining process is developed. This process is synonym with the name of wire electrical discharged turning (WEDT) which incorporates a turning process of rotating workpiece to continuous travelling electrode wire in electrical discharged conditions produced by wire electrical discharge machine. The objective of this research is to develop and evaluate the advance machinery and equipment for rotary axis mechanism that is being used to rotate the workpieces. The research focuses on optimizing the process parameter of hybrid WEDT for micro-machining straight shaft cylindrical component made of Ti6Al4V as materials. The issues pertaining to hybrid WEDT process on surface roughness (Ra) in the past have been explored comprehensively. The rotary axis mechanism that works well with WEDM machine has been successfully developed and the micro turning operations has been performed. The parameter optimization consideration on Ra begins with two stage screening. Firstly, the suitable combination parameter and its range is properly selected. Then, the selection of appropriate parameters and range is further screened by Taguchi orthogonal array  $L_{12}$ . From the 11 process parameters that consist of electrical, non-electrical and rotary axis mechanism characteristics, only four has been selected to perform optimization by response surface methodology (RSM) which are intensity of pulse, voltage open, wire tension and rotational spindle speed. The other parameters are fixed at best level to produce low Ra value which is identified by Alicona Infinite Focus microscope (IFM). The optimal Ra that is produced by experiment through desirability approach is as much as 4.0143 µm with relative error as much as 5.9% compared to the prediction. The parameter and its level are pulse intensity of 8 Notch, wire tension of 14.8 Newton, voltage of 7 Notch and rotational spindle speed of 2390 rev/min. The machined parts surface is being deteriorated accordingly to the violent energy density generated by high pulse intensity and voltage, low wire tension and spindle speed.

#### ABSTRAK

Pemesinan mikro dianggarkan memain peranan penting dalam teknologi pembuatan kini. Namun, pemesinan penskalaan kecil bagi proses tradisional adalah mencabar, ia berkait dengan kestabilan proses dan sifat bahan terutama jenis bahan sukar dimesin bahkan dalam penskalaan kecil. Oleh itu, proses pemotongan yang sesuai dalam melaksanakan pemesinan mikro pada bendakerja berbentuk silinder adalah proses cucuhan hakisan. Dalam penyelidikan ini, proses pemesinan hibrid mikro terbaru telah dibangunkan. Proses ini sinonim dengan nama pemesinan larik wayar nyahcas elektrik (WEDT) dimana ia menggabungkan putaran bendakerja terhadap wayar elektrod dalam persekitaran nyahcas elektrik yang dibekalkan oleh mesin wayar nyahcas elektrik. Objektif penyelidikan ini untuk membangun dan menilai terhadap mesin dan kelengkapan termaju bagi mekanisme paksi putar yang digunakan untuk memutarkan bendakerja. Penyelidikan ini memfokuskan pengoptimum parameter bagi proses hibrid mikro WEDT dalam pemesinan mikro komponen silinder berbentuk aci lurus yang diperbuat oleh bahan Ti6Al4V. Isu yang berkaitan proses hibrid WEDT terhadap kekasaran permukaan (Ra) pada kajian lepas telah dikaji secara menyeluruh. Mekanisme paksi putaran yang berfungsi dengan baik pada mesin WEDM telah berjaya dibangunkan dan melaksanakan operasi melarik mikro. Pengoptimum parameter untuk Ra bermula dengan dua peringkat penyaringan. Pertama, kombinasi dan julat yang sesuai diantara parameter dipilih. Seterusnya, penyaringan peringkat kedua dilakukan dengan menggunakan teknik Taguchi pada parameter dan julat yang telah dipilih. Daripada 11 parameter yang dipilih, hanya empat sahaja parameter yang dibawa dan dioptimumkan oleh kaedah metodologi permukaan sambutan (RSM) iaitu keamatan denyutan, voltan buka, ketegangan wayar dan kelajuan putaran spindel. Parameter yang lain dikekalkan pada tahap minimum terhadap prestasi Ra yang mana ia diukur oleh mikroskop Alicona Infiniti Fokus Mikroskop (IFM). Keoptimalan Ra hasil daripada eksperimen yang telah dibangunkan dengan kaedah kebolehinginan bernilai 4.0143 µm dengan ralat relatif sebanyak 5.9% apabila dibandingkan dengan nilai ramalan. Kemerosotan prestasi pada permukaan bendakerja dialami apabila keamatan denyutan dan voltan buka ditetapkan tinggi disamping ketegangan wayar yang kendur dan kelajuan putaran spindel yang perlahan.

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# LIST OF SYMBOLS

σ	-	(Sigma) units for stress calculation
μ	-	(Micro) metric unit denoting a factor of 10-6 or represent small
α	-	(Alpha) coded-unit distance for axial points in central composite design
δ	-	Deflection
df	-	Degrees of Freedom
k	-	number of factors in design
$\mathbb{R}^2$	-	Index of determination
n	- 3	number of observations in sample
Р	EKW	Probability Value
V	-	(volt) unit for electric potential difference
D	- 03	Diameter
Т	-1	Thickness
ID	2)	اويتو سيني بيڪنيڪ Inside Diameter
OD	UN	Outside Diameter NIKAL MALAYSIA MELAKA
Pa	-	(pascal) unit of pressure/stress
Ω	-	(Ohm) unit of electrical resistance
LA	-	Machine power supply low
MP	-	Machine power supply medium
HP	-	Machine power supply high
L, l	-	Length
Ra	-	Arithmetic average surface roughness

# LIST OF ABBREVIATIONS

- Three Dimension
- Annular Bearing Engineering Committee
- Alternating Current
- American Iron and Steel Institute
- Analysis of Variance
- Coefficient of Variation
- Computer-Aided Design
- Computer-Aided Manufacturing
- Central Composite Design
- Computer Numerical Control
- Cylindrical Wire Electrical Discharge Turning
- Direct Current
Electrical Discharge Machining
- Face-centred Central Composite Design
- Factor Interaction
- High Speed Steel
- In Circuit Serial Programming
- Integrated Development Environment
- Infinite Focus Microscope
- Intensity of Pulse
- International Standardization Organization
- Liquid-Crystal Display
- Light-Emitting Diode
- Liquid Quantity
- Liquid Resistivity

Μ	-	Metric
MRR	-	Material Removal Rate
OA	-	Orthogonal Array
OFF	-	Off Time
PIC	-	Programmable Interface Controllers
PRESS	-	Predicted Residual Error Sum of Squares
РТ	-	Pre-Tension
PWM	-	Pulse-Width Modulation
RSM	-	Response Surface Methodology
SA	-	Stabilizer A
SB	-	Stabilizer B
SC	-	Stabilizer C
SE	-27	Stabilizer E
SEM	EKW	Scanning Electron Microscopy
$Si_3N_4$	F	Silicon Nitride
Ti6Al4V	- 23	Titanium Alloy Grade 5
USB	Zha	Universal Serial Bus
VG	V	اويوم سيتي بيڪييڪل Voltage Gap
Vo	UNI	Voltage Open KNIKAL MALAYSIA MELAKA
WEDG	-	Wire Electrical Discharge Grinding
WEDM	-	Wire Electrical Discharge Machining
WEDT	-	Wire Electrical Discharge Turning
WS	-	Wire Speed
WT	-	Wire Tension

#### LIST OF PUBLICATIONS

#### Journals:

- 1. Izamshah, R., Akmal, M., Kasim, M.S., Sundi, S.A. and Hadzley, M., 2016. A Statistical Comparison in Selection of Wire-EDM Process Parameters for Machining Titanium Alloy. *Journal of Advanced Manufacturing Technology (JAMT)*, 10(2), pp. 45-56.
- Izamshah, R., Akmal, M. and Kasim, M.S., 2017. Improvement of the Wire Compensation Configuration Model for Improving Part Accuracy in Cylindrical Wire Electrical Discharge Turning. *International Journal of Manufacturing Technology and Management*. (In Press)(Scopus)
- Izamshah, R., Akmal, M., Kasim, M.S., and Amran, M., 2017. Emerging Hybrid Wire Electro Discharge Turning for Micro Parts Fabrication in the Defence Technological Area: A Feasibility Study. *Journal of Fundamental and Applied Sciences*, 9(3S), pp.176-188. (ISI)
- 4. Izamshah, R., Akmal, M., Amran, M., and Kasim, M.S., 2017. Parametric Study on Parameter Effects in Hybrid Micro Wire Electrical Discharge Turning. *Journal of Advanced Manufacturing Technology (JAMT)*. (Accepted)(Scopus)
- Izamshah, R., Akmal, M., Amran, M., and Kasim, M.S., 2017. Performance Evaluation of Rotary Mechanism Characteristics by Response Surface Methodology in Cylindrical Wire Electrical Discharge Turning. *Advances in Materials and Processing Technologies*. (Accepted)

#### **Proceedings:**

- Akmal, M., Izamshah, R., Kasim, M.S., Hadzley, M., Amran, M. and Ramli, A., 2016. Configuration of Wire Positioning To Minimize Parts Error in Wire Electrical Discharge Turning (WEDT), *Proceedings of International Conference on Advanced Processes and Systems in Manufacturing (APSIM 2016)*, Kuala Lumpur, Malaysia, 28-30 August 2016. National University of Malaysia Publisher. (ISI)
- Akmal, M., Izamshah, R., Kasim, M.S., Hadzley, M., Amran, M. and Ramli, A., 2016. Development of a Rotary Axis Mechanism for Wire EDM Turning (WEDT). Proceedings of Mechanical Engineering Research Day 2016 (MERD')

16), Melaka, Malaysia, 31 March 2016. Universiti Teknikal Malaysia Melaka Publisher. (ISI)

- Izamshah, R., Akmal, M., Kasim, M.S., Amran, M., Ramli, A. and Liew, P.J., 2016. Emerging Hybrid Wire EDM Turning (HWEDT) In Defence Technological Area for Micro Parts Fabrication: A Feasibility Study, *Proceedings of the Asia Pacific Conference* on Defence & Security Technology (DSTC 2016). Putrajaya, Malaysia, 15-17 August 2016. National Defence University of Malaysia Publisher.
- 4. Akmal, M., Izamshah, R., Kasim, M.S., Hadzley, M., Amran, M. and Ramli, A., 2016. Performance Evaluation of Rotary Mechanism Characteristics by Response Surface Methodology in Cylindrical Wire Electrical Discharge Turning. *Proceedings of Advances in Materials and Processing Technologies (AMPT 2016)*. Kuala Lumpur, Malaysia, 8-11 November 2016. University of Malaya Publisher.



#### **CHAPTER 1**

#### **INTRODUCTION**

#### 1.1 Research Background

Nowadays, medical and defence field have been increasingly demanding miniature devices and components with complex micro-dimension features made from various materials (Hung and Chang, 2017; Aggarwal et al. 2017; Wood et al. 2012). The high rate of patient acceptance in minimally invasive surgery and costly treatment lead miniaturization in medical devices (Packianather et al. 2016). Concomitant technology in miniature sensors and electronic devices embodying micro-manufacturing becomes one of the key sectors in defence field (Liu and Zhu, 2017; Wang et al. 2017). Emergence of micro-manufacturing in both of this field contributes to a greater precision, complex geometric features and tight tolerances and literally extend capabilities to miniaturization especially in mechanical parts which micro-manufacturing is required the most (Qin et al. 2015). Figure 1.1 illustrates the example of the miniaturized components in several of applications that depends upon micro-manufacturing.

Micro-machining is the most basic technology for the production of such miniaturized parts and components. Since miniaturization of industrial products has been the trend of technological development, micro-machining is expected to play an increasingly important role in today's manufacturing technology. Many processes may potentially be used to produce micro parts and the number of associated technologies continue to increase (Asad et al. 2007). Micro parts and micro structures can be produced by scaling up nano-scale processes, such as silicon-based technology and by scaling down conventional manufacturing processes (Razali and Qin, 2013). Between these two categories, conventional manufacturing processes such as (micro milling for three-dimensional part profile, micro turning for cylindrical part profile, micro electrical discharge machining ( $\mu$ EDM) for three-dimensional part profile and micro grinding for surface modification) are more favourable due to its flexibility, reliability and economical point of view (Anand and Patra, 2014). However, the down-scaling creates challenges relating to process stability and behaviour of the materials due to the mechanic of material removal especially for thin and tiny difficult-to-machine materials as reported by Anand and Patra (2014) and Hourmand et

al. (2016).



Figure 1.1: Miniaturized components in medical, metrology and defense applications (Janson et al. 1999; Sheu, 2004; Jee and Kim, 2011; Rees, 2011; Zhu et al. 2016)

On most of the micro-machining processes, the cutting force influences the mechanic material removal mechanism which limits the machinable size due to the physical contact between tool and workpiece. Due to the poor stiffness of the micro part feature, deformation is more likely to occur in the machining process which results in dimensional surface errors (Yi et al. 2017; Zhang et al. 2016). Micro turning appears as one of the most versatile processes and it has been producing micro-cylindrical or rotational symmetry workpieces. Unfortunately, the main barrier in micro turning process is the radial cutting force which deflects the workpieces that can significantly affect the part accuracy (Asad et al. 2007).

During the operation, the thrust force is carefully considered to control the workpiece deflection. The workpiece is easily deflected by the reacting force with a reduction in its rigidity according to the decrease in its diameter as in Figure 1.2 (Masuzawa, 2000) which will affect the machining accuracy and also limit the machinable parts size due to the elastic deformation of the micro tool and/or the workpiece. The workpieces only vibrate in the tangential direction of the tool-workpiece contact region because the vibration along the tangential direction is constrained by the cutting tool (Lim et al. 2002). In most cases, the tool is either broken or starts to wobble due to excessive radial cutting force on the workpiece (Rahman et al. 2010). Other than that, the deflection will reduce the machining accuracy, and slow down the production (Friedrich, 2002).



Figure 1.2: Workpiece deflection in micro turning (Rahman, 2004)

Therefore, a suitable material removal mechanism for the fabrication of microcylindrical part is necessitated to overcome the part of deflection problem originated from the cutting forces. One of the most suitable candidate is spark erosion based machining, in which the material is removed by using an electrical discharge energy without a physical contact between tool and workpiece subsequently eliminate the cutting forces.

# اويونر, سيتي تيڪنيڪل مليسيا ملاك Problem Statement

1.2

Turning by wire electrical discharge machining is a process that employs basis technology of the wire electrical discharge machining (WEDM) fundamentally based on the electrical discharge machining (EDM) sparking phenomenon. The nature of the WEDM process itself has been known as extremely important for machining precision components in mould and aircraft industries owing to its unique advantages such as excellent repeatability, high geometrical accuracy, minimum set-up time, complex geometries cutting and stresses free cutting (Gupta et al. 2016; Rahman et al. 2014; Davim, 2013). Recent trend in utilizing the hardened and intricate cylindrical components for various applications has

made the conventional of WEDM turns into the turning process that is known as wire electrical discharge turning (WEDT).

In WEDT, the minimum size of the axial dimension of a geometrical component is highly dependent on the diameter of electrode wire ranging from 200 µm to 500 µm. In radial dimension, it depends on the positioning of electrode wire controlled by WEDM machine itself. Despite the micro-scale of electrode wire, the capability of this process in machining micro dimension geometries of the components can clearly be seen. Incorporating the hybrid between WEDM and turning process would be beneficial in countering the part deflection as faces by micro-turning (Rahman, 2004). WEDM uses a fine metallic wire which carries the discharge energy that continuously fed from a spool through the part, keeping a constant diameter. Hence, by combining the EDM process with a rotating workpiece, they can provide an effective solution for fabricating parts with complex geometrical features that are made from material like tungsten carbide, tool steel, titanium alloys and memory shape alloys which known as difficult-to-machine materials.

Although WEDT has the potential to be a relatively process to perform the micromachining for cylindrical components, little is known about the assessing of the operating parameters of hybrid micro WEDT against the parts surface finish. Large majority of the WEDT research requires the researchers to design and develop their own rotary axis mechanism to investigate the machining characteristics of the WEDT process. The discrepancy between the results depends on the design of rotary axis mechanism itself. Any modification in machining conditions led the alteration of machining nature consequently will affect the machining performance (Janardhan and Samuel, 2010). Relevant WEDT studies of the past are limited to macro size of workpieces and the nature of machining operations also different. Practically in WEDT, the established optimized parameters of macro parts machining is unable to extend for micro-machining of cylindrical application by WEDT. Therefore, significant efforts are needed to better understand the behaviours of the hybrid WEDT operation at micro-rotating workpieces. New strategies are needed for machinery design and experiment condition. The optimal process parameter is needed for solving and fulfilling the miniaturization of components demands made by hybrid micro WEDT process.

#### **1.3 Research Objective**

The objectives of this project are:-

- i. To develop and evaluate the rotary axis mechanism that can be incorporated with the WEDM machine for micro-cylindrical components fabrication.
- ii. To identify the influences of process parameter on the surface roughness in micro-cylindrical components fabrication by hybrid WEDT.
- iii. To establish the optimum process parameter in fabrication of microcylindrical components by hybrid WEDT.

#### UNIVERSITI TEKNIKAL MALAYSIA MELAKA 1.4 Scope of Work

1.4 Scope of Work

This research focuses on optimizing the process parameter of hybrid WEDT for micro-machining straight shaft cylindrical component made of Ti6Al4V as materials. The development of rotary axis mechanism suits the WEDM machine with capability to turn cylindrical components in micro scale. The single pass approach with straight turning operation is used. Investigation of process parameter covers three kind of parameters which are electrical, non-electrical and rotary axis mechanism characteristics. Taguchi orthogonal array (OA) and response surface methodology (RSM) is employed as design of experiment method. The response surface methodology specific to Face-centred Central Composite Design (FCCD) to generate design scheme, to identify influence and interaction parameter and determine optimal machining process parameter with goal to minimize the surface roughness.

#### 1.5 Significance of Studies

The global product development landscape today has focused on microsystems-based products. With the reduction of size, cost-effective product can be realized over the use of less material, energy and storage space with desired quality. One of the difficulties associated with manufacturing small scale-components is length scale integration not to mention obtaining the excellent surface finish, where the new machineries need to be innovated to converge new and present technologies that will create new hybrid processing platforms. The research study contribute as science push type project that capable to open up an opportunity in fabrication of miniaturization product with combinatorial macro and micro dimension of free-form cylindrical components. The empirical knowledge is used to improve the process design to obtaining the best of parts surface finish, by quantifying the technical requirements and limitations of the technology, and developing new processing solutions for retaining and energizing the manufacturing sector.

#### 1.6 Organization of Report

The research is presented in five chapters, of which Chapter 1 encompasses the background of the research, followed by the problem statement of the project study, the objectives that are aimed in this study, scopes of projects, significance of the research and report organization. Chapter 2 comprises of a literature review and a summary of the previous research works. Chapter 3 begins with overview of methodology of the research by flowchart, the method of the research is embedded in this chapter covering the development

of rotary axis mechanism, materials and experimental setup, measurement instrumentation, experimental design scheme for parameter screening and optimization. Chapter 4 elaborates and discusses the result of process parameter screening and optimization. The scientific discussions are included for each of the parameters selected for optimization. The chapter concludes by analysing the empirical results and commenting on the surface roughness. The optimization through desirability approach is also enclosed in this chapter including the confirmatory experiment to validate the empirical model. In Chapter 5, the main conclusion of the research is summarized. Some possible directions for further investigations are also suggested.



#### **CHAPTER 2**

#### LITERATURE REVIEW

#### 2.1 Introduction

In this section, critical review of published work is carried out aims to achieve the following objectives:

- To provide a general review of the WEDT process.
- To identify the critical components in developing rotary axis mechanism in WEDT process.
- To interpret between electrical discharge waveform of WEDT and WEDM process.
- To identify the critical WEDT process parameters as the input parameters and its performance measures for the optimizations work.
- To clarify the work materials and challenges in machining Titanium Alloy.
- To justify the appropriate design and analysis method for the present study.

#### 2.2 Turning by Wire Electrical Discharge Machining

The earliest fabrication of cylindrical components by using WEDM has been reported by Masuzawa et al. (1985) which is recognized as wire electrical discharge grinding (WEDG). This process is known as a micro-fabrication process that employs electrical discharges in producing micro components (Morgan et al. 2003). This process imposes a travelling electrode wire between one or two guides (Fleischer et al. 2004) to confine the wire tension within the discharge area between the cylindrical workpiece and the front edge of the wire to minimize the wire vibration (Ho et al. 2004). By minimizing the wire vibration, the WEDG capable of grounding a workpiece as small as 5 µm diameter with high accuracy, good repeatability and satisfactory straightness (Masuzawa and Tönshoff, 1997). WEDG provides an advantage which is the ability to machine a cylindrical components with a large aspect ratio, maintaining the concentricity as well as capable to fabricate complex shapes such as tapered and stepped shapes (Ho et al. 2004; Fleischer et al. 2004). In WEDG, a simple resistor-capacitor circuit used to generate pulses which produces electrical discharges between the workpieces (cathode) and an electrode wire (anode) with small gap approximately 2 µm which filled with dielectric fluid. In addition, the rotation of the workpiece is held vertically in a mandrel and Z axis is served to feed the rotating workpieces towards the travelling electrode wire (Morgan et al. 2003). There are variety of components that employ WEDG such as micro nozzle (Masuzawa and Tönshoff, 1997), EDM micro electrodes (Weng et al. 2003) for EDM drilling (Masuzawa et al. 1989) and fabrication micro mould (Yu et al. 1998), micro spherical probes (Sheu, 2004), ejection pins or core for mould inserts and milling tools (Fleischer et al. 2004).

The principle of WEDT (Figure 2.1) is basically similar to the WEDG (Figure 2.2). In WEDT, the initial of the machining workpieces is not limited in cylindrical forms (Haddad and Tehrani, 2008a). The combination of rotating workpieces and movement of a thin singlestrand of wire open up an opportunity in producing intricate and hardened cylindrical components that mostly limited in traditional machining. This process also has capability to produce variety shapes including free-forms shapes (Qu, 2002). The linear cutting speed of the X-Y direction is controlled by servo mechanism and the electrode wire is constantly fed from a retaining spool to the machining gap. In addition, the retention of the wire spool is also important to ensure constant tension applied during the erosion process. In order to produce axis-symmetric of macro or micro components in WEDM, the rotary axis mechanism which capable to operate inside the dielectric fluid is attached on machine table. The clear difference between WEDG and WEDT is the principle of the WEDT does not employ the wire guide at the point of contact between electrode wire and rotating workpieces. The discharge area in WEDT is identical to the WEDG (Figure 2.3) as both processes employ electrical discharge, wire electrode and rotating workpieces. The highpressure water jet is introduced to enhance the machining performance of WEDT which comprises of improving the material removal rate (MRR) and surface finish besides maintaining the uniform thermo-environment. The flows direction of the water jet is typically the same as the direction of electrode wire travelling. This condition is capable to help in maintaining the wire electrode stability during the erosion process. During the spark erosion, as soon as material is removed by the spark, the workpiece and the electrode wire is moved closer again by mechanism from wire spooler, servo feed and rotary spindle. The electrode wire is continuously replenished in order to ensure the fresh electrode wire surface will be available for next sparks. By applying the rotary mechanism, the un-machined portion on the workpieces surface is replaced by machined portion, and vice versa. The machined portion which previously exposed to spark erosion now is open to the flushing flow for removing the excess melted material (debris).



Figure 2.2: Wire electrical discharge grinding (WEDG) a) Twin wire guided (Lim et al. 2003) b) Single wire guided (Chern and Wang, 2007)


Figure 2.3 : The phenomena of discharge area in WEDT along the electrode wire

### 2.3 Rotary Axis Mechanism for Wire Electrical Discharge Machining (WEDM)

For the several past decades, the concept of WEDM has been upgraded by adding a rotary axis mechanism and is called with various names such as wire electrical discharge turning (WEDT) and cylindrical wire electrical discharge turning (CWEDT). There are chronologies in developing this rotary axis mechanism that has become significant in the manufacturing industry. Qu et al. (2002a) has designed a rotary axis mechanism that is capable to work in submerged deionized water environment (Figure 2.4). The rotating workpieces which are clamped by R8 collet is driven by electrical motor and assisted through belts and pulleys. A pair of deep groove silicon nitride ball bearings with stainless steel rings is used to prevent the electrical discharge to occur between the gaps on steel bearing. The collet R8 also serves as terminal for electrical discharge which the electrical current is delivered from the WEDM table through a carbon brush. But, the details about the principle of carbon brush are not clearly stated. A carbon brush is a sliding contact used to transmit electrical current from a static to a rotating part.



Figure 2.4: Rotary axis mechanism develop by Qu et al. (2002a)

In 2008, Haddad and Tehrani (2008) had developed a rotary axis mechanism that equipped the WEDM machine type ONA R250 in order to produce cylindrical form parts (Figure 2.5). Coupled with Mohammadi et al. (2008), they had used direct current (DC) motor to transmit the rotary motion to the spindle with R60 collet (Figure 2.6). The special sealing is being used to prevent the debris from entering the bearing housing.



Figure 2.5: Rotary axis mechanism developed by Haddad and Tehrani (2008)



Figure 2.6: Rotary axis mechanism developed by Mohammadi et al. (2008)

Janardhan and Samuel (2010) proposed a straight shank ER 11 collet adaptor as spindle shaft (Figure 2.8) in order to minimize the run-out error in between straight shaft and a chuck or other clamping devices. They claimed a maximum of 5 µm run-out by adopting this design. The main difference between this rotary design with other researchers is the spindle and motor shaft were connected by worm gear made of plastic as shown in Figure 2.8. In addition, to improve bearing accuracy, brass cylinder has been inserted to the housing as well as to avoid the damage of housing bore during bearing installations. The carbon brush is being located along housing circumference with threaded holes. The rotary axis mechanism is being installed to Electronica EcoCut WEDM and the nylon sleeves are being used to fit on spindle shaft works with stainless steel deep groove ball bearing.



Figure 2.7: Cross-section view rotary axis mechanism developed by Janardhan and Samuel (2010)



Figure 2.8: Rear view of rotary axis mechanism developed by Janardhan and Samuel UNIVERSITI TEKNIK (2010) ALAYSIA MELAKA

The method by Janardhan and Samuel (2010) was used similar by Parthiban et al. (2013) where the motor had been isolated from spindle with ER16 collet by placing nylon sleeve between motor shaft and pulley to prevent from back current that would damage the motor. The rotating workpieces is driven by a spindle that submerged in deionized water or dielectric fluid. The oil seal is used to ensure the rotary axis mechanism would be capable of working properly in submerged environments. This rotary axis mechanism is being installed in Mitsubishi Advance FA10S and the maximum of the spindle run-out was 8 µm (Figure 2.10). Figure 2.9 shows the rotational speed of 150 Watt induction alternating current

(AC) motor that was used in range of 0 to 1350 RPM. Besides that, the usage of 12 volts with 6 Watt DC motor to generate the rotary motion to the spindle shaft was reported by Rajkumar et al. (2012). The development of this rotary axis mechanism that consists of various components such as self-centring chuck, spindle shaft, deep groove single row ball bearings, spindle housing, timing belt, flanged gears and lock nut are being installed on Electronica WEDM.



Figure 2.9: Rotary axis mechanism developed by Rajkumar et al. (2012)



Figure 2.10: Rotary axis mechanism developed by Parthiban et al. (2013)

In summary, there are three main components needed in developing the rotary axis mechanism where the first component is the rotating clamping system that hold the workpieces. The consideration of this component is that it should have high accuracy to deliver rotational motion for micro-machining practise. Then, it should allow the flow of an electrical current to the workpieces to form spark erosion. The second main component is the way to motorize the clamping system with variable speed. Third component that should be considered at the design stage is the approach to attach all the other components for ease-installation and prevent from damage by wet environment, back current and corrosion. Other design consideration that has been stressed out in the previous studies is the way to obstruct the bearing from damage by interference of machine polarities. Among all of the rotary axis mechanism that has been developed by the researchers, there is no rotary axis mechanism that focuses in machining micro part components.

### 2.4 Pulse Characteristic between WEDT and WEDM

The knowledge and understanding on pulse characteristics is of great importance since applying a rotating workpiece to the normal WEDM process has altered the nature of its principle. The discharge pulses in WEDM are categorized in three types which are normal, arc and short as presented in Figure 2.11. Normal pulses, are those that generate a spark when the voltage reaches the settled voltage level and are considered to contribute to the metal removal process (Caggiano et al. 2016). By increasing the frequency of normal pulses will increases the MRR (Janardhan and Samuel, 2010).

Arc pulses, are very unstable in terms of pulse occurrence number and energy. This type of pulses generated when the spark voltage is lower than normal pulses (Caggiano et al. 2016). If arc pulses produces frequently, the MRR will decrease (Janardhan and Samuel, 2010). Arc is characterized as a deteriorated process (Schumacher et al. 2013). According to

Liao and Woo (1997), arc pulses occur if there is discharge before the gap voltage reaches its nominal level or the level of the gap voltage for normal pulse. Typically, the actual gap voltage of arc pulses has two types of time factors which are voltage recovery time and deionized time. Voltage recovery time depends on power supply capacity and switching ability. De-ionized time indicator is influenced by the resistance of the dielectric that has been potentially affected by the gap width and the instantaneous amount of slags in the gap.

Short pulses, are those that generate a spark at lower voltage level. The occurrence of a so-called "short circuit" represents an undesired phenomenon in WEDM, since it can lead to defects on the final workpiece surface or even to the wire breakage (Cabanes et al. 2007; 2008). According to Liao and Woo (1997), short pulses occur when there is contact between the workpiece and the electrode. During this moment, a short current occurs whilst the gap voltage is loaded synchronously and no lag time between them.



Figure 2.11: Discrimination between arc, short and normal pulses in WEDM process (Liao and Woo, 1997)

Presence of the rotary axis mechanism in WEDM has changed the characteristic of the pulses, therefore there are different results reported between Janardhan and Samuel (2010) and Rees (2011) regarding pulse characteristics. Janardhan and Samuel (2010) claimed that the fluctuation of average gap voltage that occurs in WEDT is higher compared to WEDM as shown in Figure 2.12 and Figure 2.13, but both of the average gap voltage is nearly equal. Rees (2011) reported that the gap voltage namely open circuit voltage in  $\mu$ WEDM is much higher than WEDG. The reduction of gap voltage in WEDG is attributed by faster and efficient recovery of the working gap due to the effects of an amplified retraction of the electrode wire that is usually done by machine adaptive servo gap control.

By chance, there has been an agreement for both researchers regarding the presence of rotary axis mechanism in WEDM. Rees (2011) stated that the rotating workpieces lead to increase variation of the discharge channel gap and Janardhan and Samuel (2010) indicated that, there is gap reduction between the un-machined portion and faces of electrode wire because the rotary mechanism that undertook the un-machined portion on the workpieces surface is replaced by machined portion, and vice versa.

Rees (2011) also found that the pulse on time that involves rotating workpieces is higher compared to static workpieces as in µWEDM. Explanation for this phenomenon is that the static discharge channels cannot be maintained over long pulse on time such as rotating workpieces where the discharge channel is interrupted by rotary motion. Thus, discharge energy remains unchanged (Rees, 2011). Janardhan and Samuel (2010) explained that in WEDT, there is more formation of arcs and arc region occur compared in WEDM due to reduction of spark gap during erosion process. Figure 2.12 and Figure 2.13 shows the comparison of pulse trains between WEDT and WEDM process as reported and clarified by Janardhan and Samuel (2010). During the discharged, the material is removed from rotating workpieces and at the same time the wire is fed forward. Through rotary mechanism, the unmachined portion on the workpieces surface is replaced by machined portion, and vice versa. The next spark gap between un-machined portion and faces of the electrode wire is reduced.



Figure 2.12: Pulse trains for WEDT (Janardhan and Samuel, 2010)



Figure 2.13: Pulse trains for WEDM (Janardhan and Samuel, 2010)

## 2.5 WEDT Performance Measures: Surface Roughness and Material Removal Rate

In WEDT itself, the performance of the machining part is evaluated through the arithmetic average surface roughness (Ra) value. Other than that, the MRR is also being investigated by most of the researchers to promote the WEDT performance towards the machinability of workpiece type. Table 2.1 shows the performance of WEDT that has been done by previous researchers. In spark erosion processes, the Ra has strong relationship with MRR. The high MRR will produce high value of Ra. The phenomena of the relationship between Ra and MRR may be simplified as spark energy density that is increased, large volume of the workpieces surface is removed that completely produce coarser surface finish (Jameson, 2001) because wide and deep crater is formed.

			Performance Measures			
Authors Materials Measures		Ra (µm)	Material Removal Rate (mm <sup>3</sup> /min)			
Mohammadi et al. (2008)	1.7131 Cemented Steel		3.916 - 4.810	27.134 - 73.534		
Haddad and Tehrani (2008); Haddad et al. (2010)	AISI D3 Steel		5.20 - 7.48	10.453 - 14.916		
Janardhan and Samuel (2010)	Brass	Surface Roughness and Material Removal	1.56 - 4.98	3.05 - 9.75		
Aravind Krishnan and Samuel (2013)	AISI D3 Steel	Rate	2.048	0.78		
Qu (2002)	Tungsten Carbide Cobalt	يڪنيڪل مل	0.68 - 2.53	2.85 - 13.9		
UN	Brass	TEKNIKAL MAL	0.98 - 3.19 A	KA 5.7 - 29.0		
Mohammadi et al. (2013, 2016)	HSS		1.928 - 2.530	0.714 - 0.834		
Rajkumar et al. (2012)	Al/SiCp	Material Removal	-	6.99 - 14.26		
Yan and Hsieh (2014)	SKD 11 Tool Steel	Rate Only	-	7.2		
Rees et al. (2008)	Tungsten Carbide	Surface Roughness Only	0.64 - 3.20	-		

Table 2.1: The summarization of the previous studies in WEDT in dealing with materials type and the value of each performance measure

## 2.5.1 Surface Roughness

According to Griffiths (2001), surface roughness is related directly to manufacturing inherent generating mechanisms that clarifies the irregularities machine surface produced

through each of the feedrate, grit, particle, or spark. It is also expressed in terms of its height, width, and distance along the surface. The surface roughness quality of the machined parts also has the potentiality to degrade the performance of the machined parts such as performance of wear resistance, fatigue strength, corrosion resistance and strength of interference.

The surface roughness is mostly measured by arithmetic average surface roughness value which is assigned by Ra with unit  $\mu$ m. The arithmetic average surface roughness value (Ra) is based on the two dimension schematic illustration of a rough surface, as shown in Figure 2.14, and is defined as (Kalpakjian and Schmid, 2006):



Figure 2.14: Coordinates used for surface roughness measurement defined by Ra equation (Kalpakjian and Schmid, 2006)

In spark erosion process, the surface contains a molten and recasts erection with poor surface integrity and low fatigue strength. Every single of the electrical discharge intense heat is produced, causes local melting or even evaporation of the workpiece material, as result, a crater is formed on the workpiece surface. However, not all of the molten material created by the electrical discharge is flushed away by the dielectric fluid circulation, some of them re-solidifies to form an undulating terrain around the machined surface that attribute to poor machined parts surface finish (Giridharan and Samuel, 2015). The roughness average (Ra) for EDM based roughing process is from 0.8  $\mu$ m to 12.5  $\mu$ m (Youssef and El-Hofy, 2008). The finishing cuts is made by EDM process through low energy density and low removal rate. The machined surface of parts is able be improve by considering the size of craters need to be small.

### 2.5.2 Material Removal Rate (MRR)

Material removal rate in spark erosion process is defined as the amount of material that is removed in volume or weight per unit time. It reflects the quickness of the machining process. In any spark erosion process, the MRR does not only depend on the workpiece material properties such as melting point, thermal and electrical conductivity but also on the machining variables such as pulse conditions (voltage, current, and duration), electrode material, polarity of power supply and type of dielectric fluid (Youssef and El-Hofy, 2008). Therefore, the process parameter that leads to higher MRR is important for production.

Theoretically, by increase in peak current leads to the increase of the volumetric MRR by successive production of spark that form wide and deep crater. These results certify the fact that, by increase in the peak current leads to the increase in the rate of heat energy and inadvertently rise the rate of melting and evaporation (Davim, 2013). Nevertheless, after a certain value, the MRR and the machining efficiency is decrease because of the occurrence of the arcing.

### 2.5.3 Influences Pulse Characteristics on WEDT Performance Measures

Typically, every type pulses trains contributes to the energy that is produced per unit time at every single discharge during erosion process. The higher the energy spent, the wider and deeper craters formed. Janardhan and Samuel (2010) found that the Ra in WEDT is influenced by the occurrence of arc regions, width of arc and normal discharge regions and average ignition delay time. The surface finish can be improved by decreasing the number of arc regions per unit time and an increase in the average ignition delay time. MRR is influenced by variation in total number of discharges and the type of discharge. The MRR in WEDT is less than WEDM at all pulse off times which explains that this phenomenon is consequence from increase number of the arc pulses. Generally, the arc pulses will reduce the MRR and normal spark pulses increase the MRR (Janardhan and Samuel, 2010). Rees (2011) claimed that the parameter that achieves excellent surface finish in WEDG is not capable to produce same surface finish in µWEDM due to the reduction of the discharge energy.

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### 2.6 **Previous Studies: Influence of WEDT Process Parameters**

Since WEDM has been able to do machining of the cylindrical components, the process parameters and performance measures that are currently investigated by various researchers in their research work is shown in Figure 2.15. Table 2.2 summarizes the process parameters that is studied by previous literatures in field of WEDT for machining macro–size components. This section directly covers the high influence of WEDT process parameter to the Ra, MRR and indirectly cover dimensional accuracy due to the accurateness of parts dimension depending on MRR.



Figure 2.15: Process parameters and performance measures of WEDT process



Pro Par	cess ame	Authors ters	Mohammadi et al. (2008)	Haddad and Tehrani (2008); Haddad et al. (2010)	Janardhan and Samuel (2010)	Qu (2002)	Rajkumar et al. (2012)	Rees et al. (2008)	Yan and Hsieh (2014)	Aravind Krishnan and Samuel (2013)	Mohammadi et al. (2013, 2016)
		Pulse Off Time (µs)	IN.	A 40.0	•			٠		•	
	Ι	Pulse On Time (µs)				•	•	•			•
	ica	Power (Ampere)	•	• 15							•
	ctr	Voltage (v)	•	•							•
Fle	Εle	Gap Voltage &									
		Voltage (v)									
ters		Servo (v)	•							•	
met		Flushing Pressure						•			
ara		(kg/cm <sup>2</sup> or bar)									
$\mathbf{P}_{\mathbf{i}}$		Wire Tension (Kgf)	•						*		
Second	al	Wire Speed (m/min)	no em								
Pro Non-Electric	tric	Spark Gap Distance								•	
	lec	(µm)									
	on-E	Ultrasonic Amplitude (µm)									•
	Ž	Servo									
		Feed/Feedrate			•	•			•	•	
		(mm/min)									
		Rotational Spindle	•	•	•	•	•	•			•
		speed (rev/min)									

Table 2.2: WEDT process parameters in existing literatures

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### 2.6.1 Pulse Off Time

In WEDM, pulse off time is defined as the time when voltage is stop being applied to the gap between the workpiece and the electrode wire (Ghodsiyeh et al. 2013). During that time, the re-ionization of the dielectric has taken place (Singh and Singh, 2012). The advantage of the pulse off time is that it is able to increase the surface finish as well as prevent wire breakage due to the short circuit that occurs because the discharged debris is difficult to be removed during the sparks erosion in the gap. Short circuit caused by debris bridging in the gap between the tool electrode and the workpiece (Prihandana et al. 2012). However, insufficient pulse off time can lead to erratic cycling and retraction of the advancing servo which reduces the operation cycle (Kumar and Choudhury, 2007). In WEDT, this parameter is highly focused among the researchers regarding the phenomenon between the pulse off time towards the results of the Ra and MRR. There has been agreement among the researchers regarding the effect of pulse off time towards all the performance measures. The shorter pulse off time is able to reduce the MRR and Ra. Haddad et al. (2009); Haddad and Tehrani (2008a); Haddad et al. (2010); Haddad (2014); Mohammadi et al. (2008); Janardhan and Samuel (2010) claimed that pulse off time has significant effects on Ra and MRR. Janardhan and Samuel (2010) stated that shorter pulse off time produces wide craters which leads to the increase in the Ra and MRR value as increase in number of discharges per unit time.

## 2.6.2 Pulse On Time

Electrical discharge only occurs during pulse on time but if the duration of the electrical discharge is too long, short circuits may occur which results to wire breakage (Ghodsiyeh et al. 2013). Besides wire breakage, MRR also increases and causes the poor

surface finish on the workpieces surface (Lee et al. 2003). In WEDT, this parameter also has been studied by several researchers in order to understand the effects of the pulse on time on Ra and MRR. The shorter pulse on time able to create fine surface finish due to smaller craters produced (Qu, 2002). In MRR, the higher pulse on time produces wide and deep craters that leads to high MRR (Qu, 2002; Rajkumar et al. 2012).

#### 2.6.3 **Power**

Muthuramalingam and Mohan (2015) has proven most of the research works revealing that the discharge current is the most influencing nature on EDM performance. Basically, the peak current is one of the important parameter in WEDM. Peak current is recognized as the amount of power used in WEDM which measured in unit of amperage and it will increase until it reaches a pre-set level during pulse on time. The maximum amount of amperage is influenced by the area of cut surface where the higher amperage normally employed in roughing operations such as in die sinking and WEDM processes (Ghodsiyeh et al. 2013).

In WEDT, peak current is synonym as power or pulse intensity which has been investigated by all the researchers in this field and indicates power as a level where there is a corresponding average current between electrode wire and workpiece. Power has significant effects and directly proportional to the Ra and MRR value as reported by all the researchers that studied on this parameter. In order to produce maximum MRR, power should be set as high as possible but it will create poor surface finish (Mohammadi et al. 2008b; Haddad and Tehrani, 2008b).

#### 2.6.4 Voltage

Generally, voltage has similar trends like power. By increasing the voltage during machining, it will lead to increase value of Ra and MRR (Haddad and Tehrani, 2008b; Haddad et al. 2009, 2010; Haddad, 2014). In contrast, Mohammadi et al. (2008) indicated that voltage is not significant on all the performances measures.

### 2.6.5 Servo Feed

Servo feed is defined as the feedrate of the machine table during machining. Usually, this parameter is selected based on the servo voltage parameter but it is still able to be set manually (Ghodsiyeh et al. 2013). In WEDM, the linear cutting speed of the machine is controlled by the servo mechanism which make the wire electrode will be continuously replenished to feed for fresh electrode wire surface. However, in WEDT, the rotational spindle speed is interfered in controlling the feed for fresh wire electrode and control the spark gap. Qu (2002) used wire speed as a term to indicate the feedrate of the machine table and he concluded that lower wire speed able to generate smaller pitches on the cylindrical workpieces surfaces which results to lower Ra. Janardhan and Samuel (2010) stated that the result of the Ra is directly proportional to servo feed due to energy per unit time. If servo feed increases, the energy per unit time will also increase thus increasing the Ra and MRR. But, servo feed has little effect on MRR by increasing slightly with increase in servo feed. Furthermore, Yan and Hsieh (2014) reported that MRR increases almost linearly with the increase of the feedrate of the machine table but at certain level the MRR starts to decrease due to the occurrence of the short circuits.

### 2.6.6 Rotational Spindle Speed

Apart from the electrical process parameters, the attachment of rotary axis mechanism in conventional WEDM should change the behaviour of the WEDM machining characteristics. The following works in investigating the effect of the rotary axis mechanism in WEDM has been reported in performance measures perspective like Ra and MRR. As reported by Mohammadi et al. (2008a) and Rees et al. (2008), the rotational spindle speed has no significant effect to the Ra. In contrast, Haddad and Tehrani (2008a); Haddad et al. (2010); Haddad (2014) stated that the rotation spindle speed has a significant effect on the Ra. As rotation of spindle speed increases, the Ra decreases.

Janardhan and Samuel (2010) reported that rotational spindle speed has very less influence on Ra for brass where the Ra value slightly decreases when the rotational spindle speed is increased from 40 to 100 rpm. Qu (2002) claimed that the Ra value reduces by increasing the rotational spindle speed for brass and carbide. But at certain value of high rotational spindle speed, the Ra is slightly higher probably due to the vibration at higher rotational spindle speed which affects the result of Ra.

In term of MRR, only Haddad et al. (2009) stated that effects of rotational spindle speed exhibit no significant on MRR. Based on Janardhan and Samuel (2010), they investigated the three value indicated the low rotational spindle speed, medium rotational spindle speed and high rotational spindle speed with 40, 70 and 100 RPM respectively. They found that by increasing the rotational speed from 40 to 70 RPM, the MRR increases from 5.89 to 6.84 mm<sup>3</sup>/min but when the rotational spindle speed is increased from 70 to 100 RPM, the value of MRR reduces from 6.84 to 6.44 mm<sup>3</sup>/min due to the accretion in the number of arcs and arc regions. Mohammadi et al. (2008b); Mohammadi and Tehrani (2008) claimed that rotation spindle speed has a significant effect on the MRR by increasing

rotational spindle speed, MRR will decrease. Increasing the rotational spindle speed will cause distort gap equilibrium (Mohammadi et al. 2008b). Rajkumar et al. (2012) stated the low rotational spindle speed leads to higher MRR because the low rotational spindle speed effectively improves the circulation of the dielectric fluid in the spark gap as well as it may increase the temperature concentration on the workpiece surface which results to the increase of the MRR.

### 2.6.7 Wire Tension

Wire deflection can occur due to the spark induced reaction forces and dielectric flushing pressure. Thus, the function of the wire tension is to prevent the wire deflection from its straight path (Malik, 2014). In WEDM, identifying the correct wire tension is mainly important to maximize the machining accuracy. The wire tension will affect the corner error, belly, vibrations and deflections. If wire tension is too high, the chances of wire break is high due to the impact between the heat and the attack of the spark upon the wire cross-sectional area. Mohammadi et al. (2008b) investigated the effects of wire tension in machining cylindrical components in WEDM towards MRR and Ra. The result indicated that only MRR has significant and inverse effects compared to Ra value. But there still has been an influence in achieving the low value of the Ra.

### 2.6.8 Spark Gap

Janardhan and Samuel (2010) concluded that the spark gap is the parameter that influences the gap resistance. Spark gap is known as the gap distance between electrode wire and the workpieces which is measured in unit  $\mu$ m. By increasing the spark gap, the MRR

and Ra value are reduced due to the reduction in the total number of discharges during the machining process. When the spark gap is increased, the depth of the craters that form is reduced. This is one of the reason for MRR and Ra becomes lower.

### 2.6.9 Summary of Process Parameters in WEDT

In summary, all the electrical type of the parameters in WEDT has influences the pulse characteristics that contributes in generating the sparks energy to erode the materials. Some of the non-electrical parameters indirectly has effects to the sparks energy such servo feed and spindle speed. By incorrect controlling this type of parameters, lots of arc and short pulses will generates because of imperfection in sparks gap. The surface roughness and MRR increases by occurrence of violent sparks that potential generated by electrical type of parameters also with less of electrode wire tension. The electrode wire easily deflects during machining when the low wire tension is applied.

## 2.7 Surface Quality of WEDT Workpieces MALAYSIA MELAKA

Despite such interest in improving the performance measures by WEDT, microstructural changes on the machined surface induced by the process is important to provide better understanding. Qu (2002); Haddad and Tehrani (2008a); Haddad et al. (2010), examined the surface of cylindrical workpieces machined by WEDM and found the surface has experienced the occurrence of ridges.

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### 2.7.1 Macro-Ridges

In EDM, the surfaces of the workpieces after machining are isotropic and there is no specific texture or pattern. However, Qu (2002) found that there is occurrence of macro-ridges or circular arcs on WEDT workpieces. The increase of table feedrate at constant rotational spindle speed generates larger pitches as well as surface roughness value (Qu 2002). Haddad and Tehrani (2008); Haddad et al. (2010) also agreed and they found similar occurrence of macro-ridges on workpieces surfaces which consist of circular arcs (Figure 2.16) with the same pitch and radius of circular arc in ideal surface that is modelled by Qu (2002).



Figure 2.16: SEM micrographs of macro-ridges and ideal arcs on WEDT workpieces machined surface (Haddad et al. 2010)

### 2.8 Titanium Alloy

In the past decades, a broad level of titanium-based materials has been developed for a wide range of applications. Titanium and its alloys are currently discovered with extensive use in many industries for fulfilling variety of components due to their combination of good mechanical and chemical properties. Incitement of titanium alloys development during the past sixty years initiated by aerospace industry when there was crucial seeks for new materials with higher strength to weight ratios.

Titanium alloy grade 5 (Ti6Al4V) is the primary candidate materials among titanium alloy family in the aerospace, power generation and medical device and even automotive industries due to its high strength to weight ratio, corrosion resistance, fatigue resistance, and capability to work in elevate temperature (Kumar, 2014). Ti6Al4V has the following chemical composition (% by weight): Aluminium, 6.9; Vanadium, 4.1. The content of impurities should not exceed (% by weight): Carbon, 0.10; Iron, 0.30; Silicon, 0.15; Oxygen, 0.20; Nitrogen, 0.05; Hydrogen, 0.015 (Moiseyev, 2005; Sha and Malinov, 2009). In terms of miniaturization parts, Ti6Al4V is widely used in medical as devices or surgical instruments. Example of miniaturized Ti6Al4V components are stents, catheters (Niinomi, 2004) and coupler micro-pin as shown in Figure 2.17 with 0.25 mm of diameter (Jee and Kim, 2011).



Figure 2.17: Microvascular anastomosis micro ring-pin system (Jee and Kim, 2011)

### 2.8.1 Challenges in Machining of Titanium Alloy

In contrast, the application of Ti6Al4V is limited due to the high price and unresolved machinability issues. Ti6Al4V comprises of low elasticity modulus, poor thermal conductivity, chemical reactivity, and hardening properties that requires an appropriate cutting tool and its optimum process parameter when machining by conventional process such as milling and turning (Davim, 2013). Table 2.3 summarized the difficulties in machining Ti6Al4V that encountered by the several of the researchers in conventional machining.

Authors	Type of Difficulties	Descriptions
Konig (1978)	High Stresses at the Cutting Interface	About 80% of the heat generation conducts into the cutting tool causing much higher level of stresses than the value obtains in case if machining steel. The higher value of heat generation represents severe plastic deformation at shear plane and severe contact conditions at the rake face of the tool resulting in higher cutting pressures.
Pervaiz et al. (2014)	High Hot Hardness and Rapid Strain Hardening	Cutting temperature increases during cutting operation but Ti6Al4V maintain their strength that results in rapid deterioration of cutting tool material and shorter tool life.
Konig (1978)	Poor Heat Dissipation	Approximately 80% of the heat generated during machining of Ti6Al4V is transferred to the cutting tool due to low thermal conductivity of workpiece and fast flowing chip removal cannot take heat away from the cutting zone.

Table 2.3: The challenges in machining Ti6Al4V by conventional machining

		During machining phase cutting tool bounces		
		back like a spring because of high elasticity of		
Davim (2010)	Self-Induced Chatter	Ti6Al4V. This bounce back action reduces		
		clearance angle on flank face which facilitates		
		chatter during the machining process.		
		Due to high chemical reactivity of titanium alloys		
Canter (2009)	High Chemical	chips tend to weld at tool tip and cutting edge		
	Reactivity	which results in crater wear, catastrophic tool		
		failure, and severe edge chipping.		

EDM based process is an alternative for conventional process for machining Ti6Al4V since there are less of cutting forces involved. There is no any direct contact between electrode (tool) and workpiece thus the problems by contact issues such as the mechanical stress, chatter and vibration problems are eliminated during machining process (Ho et al. 2004).

During machining by WEDM, the Ti6Al4V temperature rises consequently by low thermal conductivity and high chemical reactivity properties that cause wire breakage (Nourbakhsh et al. 2013). The wire breakage during machining has an important and direct effect to the process performance not to mention in WEDT as well. In WEDT, none of the previous studies has investigated the machining of Ti6Al4V likewise for micro-scale part components.

### **2.9 Design of Experiment (DOE)**

Design of experiments (DOE) is a systematic technique in identifying the relationship between input factors affecting a process and the output of that process. DOE replaced and became as an alternative approach for one factor at time (OFAT) with aid of statistical tools and experimentation concepts (Myers et al. 2009). OFAT serves useful to determine main effect of each variable to the output response. However, for a complex system, the conventional OFAT still lack in time-consuming, non-feasible and incompetent to obtain true optimum condition because lack of interactions among the variables. This technique is also inadequate for model building and optimization when works in the system indistinct of reaction mechanism.

In particular, Taguchi orthogonal array (OA), factorial and response surface methodologies (RSM) have been successfully applied as design of experiment techniques in both discovery and development. Most of the comprehensive approach of DOE begins with 'screened' to determine which are important factors to the output of the process then followed by 'optimization' to identify the best settings for the important variables (Pandey, 2013).

According to Anderson (2016), smaller factors range will provide better results in obtaining the best fits of polynomial model for optimization. They suggested to use the matter knowledge and results from prior screening designs as indicated in Figure 2.18 to select factors and ranges that frame a region of interest, which expect to find the ideal response levels. For example, as shown in Figure 2.18, it may be possible to operate over a very broad region of the input x. Perhaps by collecting enough data and applying a higher degree of polynomial, the model surface shown also easier to be obtain. Practically, most of the objective of DOE is to obtain a model that works well within the smaller region of interest where performance (y) peaks. If the field of factors is narrowed within its vital range, the study will be more specific and therefore, the selection of the quadratic level becomes less for the power of x for the predictive models.



Figure 2.18: Region of interest versus region of operability (Anderson, 2016)

## 2.9.1 Taguchi Orthogonal Arrays (OAs)

The Taguchi technique is known as a comprehensive method to provide effective application of engineering strategies compared to the advanced statistical techniques. This method is widely used by experimental works in area of design and manufacturing processes in order to reduce variability, provide cost-effective, and robust designs (Nourbakhsh et al. 2013). In developing appropriate operating condition level and weightage among the control factors, it is necessary to spend huge effort and cost. By initial screening and rationalization purposes, the fractional factorial approach become more realistic in evaluation of machinability by experimental works with significantly fewer tests but provide acceptable confidence. Taguchi method recommends the Orthogonal Arrays (OA) in conducting the experiment to obtain effective systematic vary and less number of experiment in evaluating the different levels of each of the controlled factors compared to the full factorial design. The most likable use of the Taguchi OA in conducting the experiment are L4, L9, L12, L18 and L27. According to Ross (1988), there are three objectives of using this Taguchi method,

which are to generate the best or the optimum condition for a product or process, estimate the contribution of individual parameters and its interactions as well as to estimate the response under the optimum condition.

Taguchi technique has found successful in various manufacturing application. Choi et al. (2016) conducted the experimental work employed by Taguchi  $L_{12}$  for design scheme in evaluating the operating conditions such as current, machining time and electrode gap for electrochemical polishing on stainless steel 316L. The result of the experiment indicates that the surface quality of the stainless steel 316L plates is improved. They agreed that by applying Taguchi method, the examining between multiple factors is effective besides significantly reduces time of the experimental works. Other than that, Shyha et al. (2009) stressed that in establishing the comprehensive operating parameters levels and contribution for one/more factors requires extensive and expensive testing such as time, labour and materials. The acceptable and confidence can be shed on the Taguchi OA technique. The researchers employ an L<sub>12</sub> Taguchi OA with analysis of variance (ANOVA) in evaluating the main effects of drill bit geometry and process parameter towards tool life and hole quality. They successfully identified the best level for process control factors in drilling process of small hole on 3 mm thick CFRP. Lodhi and Agarwal (2014) employed Taguchi technique in investigating the machining conditions for Ra in cutting AISI D3 steel by WEDM. This design effectively reduces the experimental sample size and determines significant factors quickly besides able to generate a set of optimal operation conditions for good quality performance by calculating the S/N ratio.

For identifying the optimum conditions by Taguchi method, the main effect of each of the parameters is investigated to develop effects and trends of the main parameter to the performance measures. This positive aid contributes to better understanding among the process parameter and become a key for controlling the nature on a production process. Furthermore, the ANOVA is also being employed to determine the percent contribution of each parameter by comparing it to the statistical confidence level condition. ANOVA provides better statistical decision for parameter control that gives priority to the performance measures.

In the analysis of the experimental works by Taguchi method, there are two different approaches, first by using the average of repetitive runs that are treated by main effect and ANOVA also known with the name of raw data analysis. Second approach is by performing multiple runs and are treated by signal-to-noise ratio (S/N) for the same steps in the analysing stage (Roy, 2010). Signal-to-noise (S/N) ratio is also known as ratio of average on standard deviation and is a concurrent quality metric that related to the loss function (Barker, 1990). Taguchi employs signal-to-noise (S/N) ratio to maximise the robustness of the operating conditions. The loss function is able to be minimized by maximizing the value of the S/N ratio. There are three cases of S/N formulation which are the bigger value, the smaller and the nominal value of the quality characteristic is better.

## 2.9.1.1 S/N Ratio

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In Taguchi technique, signal-to-noise (S/N) ratio divides the response of the factors to main categories which are control factors and noise factors (Taguchi et al. 2005). The control factors are the controllable process variables which the product becomes useless without and noise factors are uncontrollable factors that contributes to variation in the response characteristic where the smaller noise factors are desirable. Taguchi interprets the noise factors by defining a loss function to imply that a loss is caused instantly by variation of response from the desired target value. This quality loss function is basically used to obtain the characteristics of nominal-the-best, smaller-the-better and larger-the-better. According to Taguchi et al. (2005), nominal-the-best is specified as a finite goal to achieve,

smaller-the-better is referred as desired output response with minimum result, with the ideal target being zero and larger-the-better output response is the type where it is desired to maximize the result, the ideal target being infinity. To attain the characteristic of responses variable, the S/N ratio is used. There are three different S/N Ratio suggested by Taguchi according to quality loss function, which are: (Jugulum and Samuel, 2010)

The data points be  $y_1, y_2, \dots, y_n$ 

$$T = Sum of data = \sum_{i=1}^{n} y_i \qquad (2.2)$$

 $S_m = Sum \ of \ squares \ due \ to \ mean \ = \ \frac{T^2}{n}$  (2.3)

$$V_{e} = Mean \, square \, (variance) = \sigma_{n-1}^{2} = \sum_{k=1}^{n} \frac{(y_{i} - \bar{y})^{2}}{n-1}$$
(2.4)  
$$S/N = \eta_{dB} = 10 \log \left[\frac{\frac{1}{n}(S_{m} - V_{e})}{V_{e}}\right]$$
(2.5)

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$$\left[\frac{1}{n}\frac{(S_m - V_e)}{V_e}\right] = 10 \log \left[\frac{1}{n}\frac{(T^2 - \sigma_{n-1}^2)}{\sigma_{n-1}^2}\right]$$
 (2.6)  
$$= 10 \log \left[\frac{T^2}{\sigma_{n-1}^2}\right]$$
(2.7)  
$$= 10 \log \left[\frac{y^{-2}}{\sigma_{n-1}^2}\right]$$
(2.8)

Or, the nominal-the-best S/N ratio can be expressed as:

$$S/N = \eta_{dB} = 10 \log\left[\frac{1}{V_e}\right] = 10 \log\left[\frac{1}{\sigma_{n-1}^2}\right]$$
 (2.9)

The equation highlights that the error variance  $(V_e)$  is an unbiased estimate of  $\sigma^2$ . The higher the S/N becomes, the smaller the variability. Maximizing this S/N is equivalent to minimizing standard deviation or variation.

Smaller-the-better:

$$\frac{S}{N} = \eta_{dB} = 10 \log \left[ \frac{1}{\frac{1}{n} \sum_{i=1}^{n} y_i^2} \right] = 10 \log \left[ \frac{1}{\bar{y}^2 + \sigma^2} \right]$$
(2.10)

Maximizing this S/N is to minimize the mean and standard deviation.

Larger-the-better  

$$\frac{S}{N} = \eta_{dB} = 10 \log \left[ \frac{1}{\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2}} \right] = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right) \quad (2.11)$$
Maximizing this S/N is to maximize the mean and to minimize standard deviation.

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## 2.9.1.2 Analysis of Variance (ANOVA)

ANOVA is a statistical method that is beneficial to detect whether there are any difference in the average performance of group tested parameter. Normally, ANOVA that works together with Taguchi OA is carried out in the same manner as other structured experiments. The standard of the ANOVA is useful on S/N ratio which is capable to identify the significant parameters based on the difference upon mean and variation. ANOVA evaluates the significance of all main factors and the interaction between them by comparing mean square to the experimental errors estimation at specific confidence levels. The sum of the squares is calculated by obtaining average S/N ration for each parameter ( $SS_i$ ) then

divided by the total sum of squares (SS). Therefore, the percentage of the contribution of each parameter that show the significant parameters influence the quality characteristics.

$$SS = \sum_{i=1}^{k} \left( (S/N \ ratio)_{i} - \overline{S/N \ ratio} \right)^{2}$$
(2.12)

$$SS_{i} = \sum_{j=l}^{l} T_{j} \times \left( (S/N \ ratio)_{i} - \overline{S/N \ ratio} \right)^{2}$$
(2.13)

$$P_i(\%) = \frac{SS_i}{SS} \times 100$$
 (2.14)

In the above formula, k is the number of the tests in Taguchi design, S/N ratio is the average S/N ratio, i is the number of the parameter levels and  $T_j$  is the number of the tests of the ith factor at the jth level.

## 2.9.2 Response Surface Methodology

One of the goals of RSM is to design optimization while reduces the cost of expensive analysis methods (Webster, 2002). Moreover, the sufficient collected data is able to develop a model for certain process that can be manipulated mathematically to predict system behaviour within some region of the design space and generate a map of response, either in the form of contours or as a 3-D rendering (Anderson and Whitcomb, 2016).

According to Myers and Montgomery (2002), the response surface design should not be performed at the early stages of modelling. The negligible factors are required to be removed from RSM design scheme and significant interactions must be identified before performing in-depth analysis. The relationship between the input factors and output responses is identified by using regression analysis in form of a polynomial equation. Myers and Montgomery (2002) stated that the RSM is necessitated when involving a higher order polynomial model such as quadratic or cubic precisely estimate the response. Table 2.4 shows the linear, quadratic and cubic polynomial equations respectively.

Туре	Equation
Linear model:	$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k + \in$
Quadratic model:	$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \beta_{ij} x_i^2 + \sum_{i < j} \sum \beta_{ij} x_i x_j + \epsilon$
Cubic model:	$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i < j} \sum \beta_{ij} x_i x_j + \sum \sum \sum_{i < j < k} \beta_{ijk} x_i x_j x_k$

Table 2.4: The polynomial equation model in RSM

The least square technique is equipped to compute the vector that makes the regression model most accurately estimated the true response behaviour and such of that the sum of the squares of the errors is minimized (Abd Rahman, 2009). The good regression model is determined by the model that must fit experimental data accurately, each effect must be statistically significant and the assumptions on input data must be valid. The evaluation for the behaviour of response of selected polynomial model is fitted by reducing the residual error. The residual is the difference between the actual experimental value and the theoretical value from the regression model. The method of least squares calculates the regression model parameters that minimize residual sum of squares or error sum of squares (SSE). Before agreeing to any model as true predictor of the response, it is essential to perform additional statistical tests on the model such as analysis of variance (ANOVA) approach where tests for significance of the regression model, significance of individual model coefficient, and lack of fit are performed (Steppan et al. 1998). ANOVA is a statistical method, based on the F-test that computes the significance of experimental effects. It

involves segmenting the total variation of a set of data into component parts (Anderson and Whitcomb, 2016).

ANOVA requires that the model of errors must be independent and normally distributed with mean zero and variance. The test for significance of regression determines if there is a linear relationship between the response and some subset of the independent variables. The null hypothesis is rejected and it means that factor gives significant effect towards response when P-values are less than 0.05 of confidence level. It means, when the model P-value is less than the significance threshold, then the null hypothesis  $H_0$  is rejected, and the regression is managed to be significant. The F-test relies on the P-values and the chi-square distribution. The significance of the model might increase as the F-value increases. Moreover, the greater the F-value and far-off from 1, the P-value becomes smaller.

## 2.9.2.1 Central Composite Design (CCD)

According Myers et al. (2009), central composite design (CCD) is a proficient design because it is ideal for in sequence experiment besides permits a reasonable amount of information for evaluating the lack of fit without concerning of an uncommon large number of design points. The CCD also provides a solid basis for developing response surface plot by offering an adequate experiment trial to fits a quadratic polynomial (Anderson and Whitcomb, 2016). A central composite design encompasses twice as many of star points depending on the factors in the design. The axial distance is basically assigned by alpha symbol and calculated in terms of coded units. Axial points are also commonly referred to star points. Axial points are points that are placed at a specified distance  $\alpha$  from the design centre in each direction on separate axis defined by the coded factor levels (Figure 2.19). In CCD, second-order rotatable experimental design consist a 2<sup>k</sup> factorial design augmented with 2k axial points and a few of centre runs which suggest three to six at zero levels for estimation of curvature and the reproducibility of the data (Voyer, 2003). The replication of the experiment at the centre points is necessary to establish an independent prediction of the experimental error. The factorial design and centre points only afford to generate a first-order model, with aids of the axial points, the quadratic terms in the model is getting produced. Figure 2.19 illustrates a central composite design with k=3.



Figure 2.19: Central composite design for three factors (Voyer, 2003)

Face-centred central composite design (FCCD) is a kind of CCD that alters the position of axial points at the centre of the faces which coded with distance of  $\alpha$  equals to 1, rather than outside the faces as in the case of a CCD (Myers et al. 2009). FCCD is applied when the region of interest and operability is coincided as mentioned by Whitcomb and Anderson (2004). The factors  $\alpha$  provides the distance of the axial points from the design centre when the design factors are defined on a coded scale such that -1 for low level and +1 for high levels of the factorial design. All factorial and axial points then lie on a cube, Figure 2.20 illustrates the FCCD for k=3.



Figure 2.20: Face-centred central composite design (FCCD) for three factors (Voyer, 2003)

#### 2.9.2.2 Application of RSM in Process Optimisation and Modelling

It is witnessed from literatures that RSM is highly efficient for various manufacturing applications. Sivaprakasam et al. (2014) successfully developed prediction model performances of MRR, kerf width and Ra by using RSM with CCD in machining of Ti6Al4V by micro WEDM process. Kumar et al. (2016) effectively produced empirical model that explain the effect of process parameters on performance characteristics only with employing FCCD in machining nickel based alloy by WEDM. By aid of the desirability approach, the optimal combination of parameters is suggested for multi-optimized objective of lowest Ra and high cutting speed. In WEDT process, Mohammadi et al. (2016) solved conflicting yields in MRR, surface finish and roundness by employing a FCCD scheme with average error merely 7% in evaluation of assistance of ultrasound to the WEDT process.

### 2.9.2.3 Optimization using Desirability Function

RSM is broadly used for process optimization recently, because it requires small number of systematic runs that capable to reduce the time, cost and resources but allows the contribution of large amounts of information from a small number of experiments. The desirability function approach in RSM becomes one of the extensive methods in industry to
cope with the optimization either in single or multiple response. According to Whitcomb and Anderson (2004), desirability ( $d_i$ ) is a utility function that varies between 0 and 1, where = 0 if the response is in an unacceptable range, = 1 if the response is ideal. The desirability equation is stated in equation below.

$$D = (d_1 \times d_2 \times ... \times d_n)^{\frac{1}{n}} = \left(\prod_{i=1}^n d_i\right)^{\frac{1}{n}}$$
(2.15)

In desirability function approach, there are three different equations that is suggested by Myers et al. (2009) according to specific scenarios for the response (y). The equation are:



The smaller the better

$$d = \begin{bmatrix} 1 & y \le T \\ \left(\frac{U-y}{U-T}\right)^r & T < y \le U \\ 0 & y > U \end{bmatrix}$$
(2.17)

The larger the better

$$d = \begin{bmatrix} 0 & y < L \\ \left(\frac{y - L}{T - L}\right)^r & L \le y < T \\ 1 & y \ge T \end{bmatrix}$$
(2.18)

T is the target, U and L represent upper and lower specification, and r,  $r_1$ ,  $r_2$  are the weights where the weights are presumed as 1 to obtain linear desirability functions as shown in Figure 2.21. The figure also illustrates the individual desirability functions for simultaneous optimization.



Figure 2.21: The scenarios for the response (y) (a) 'the larger the better', (b) 'the smaller the better', (c) 'the target is the best' (Myers et al. 2009)

## 2.10 Concluding Remarks

Based on the literatures, most of the studies highly focused to the macro scale of machining part dimension. What is known about WEDT is, it works in the same manner as WEDM that has opened up an opportunity in machining hardened and cylindrical shapes workpieces. Despite the micro-scale of electrode wire and high accuracy of X/Y motion platform of WEDM machine itself, WEDT has the potential to bring dramatic changes in capability range in machining of micro geometries. But, little is known about the capability of WEDT in machining down micro scale of cylindrical parts. Other than that, huge number of WEDT research requires the researchers to design and develop their own rotary axis mechanism to investigate the machining characteristics of the WEDT process which led to variation of the design and its performance. None of the previous studies proposed the design of rotary axis mechanism that is capable to turn the micro scale of cylindrical parts components. Therefore, the interference of rotating workpieces with the electrode wire in microscale machining, likely has altered in pulse characteristics as found in WEDT for macro scale that can affect the performance measures such as parts surface finish. The existing knowledge in understanding the influence process parameter for macro-scaled WEDT thought will change. The need for suitable process parameter for this specific process is vital to contribute better knowledge for researchers and the machinist to stimulate the world demand growth of hardened cylindrical components for modern applications.

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#### **CHAPTER 3**

#### **MATERIALS AND METHODS**

#### 3.1 Introduction

This chapter emphasizes the way of the research work is conducted as illustrated in Figure 3.1. In general, this research work is divided into three major stages. Each of the stages begun by deep literature surveys on established theories and practices of WEDT starting from the basic WEDM process until the behaviour of rotating workpieces in WEDT, not to mention deeper fundamental electrical discharges knowledge regarding pulse characteristics. Subsequently, the objectives of the research are identified and proposed together with the scopes of works. The similar WEDT process progressive development to machining micro-cylindrical components that offers advancement in miniaturization is then proposed to be investigated in the manner of fabrication process to establish the comprehensive parameter optimization.

The first stage has covered the design and development of rotary axis mechanism. The rotary axis mechanism is developed to work together with WEDM machine. The design of rotary axis mechanism is proposed and illustrated with computer-aided design (CAD) model including the details of the subparts. Each of the part designs that has been selected is referred to the literature surveys. Most of the part and subpart is commercialized type which has the advantage to be replaced if worn or tore. The mechanical parts, hardware, software namely rotary spindle and speed controller are built, integrated and assembled together that will be described later. The complete rotary axis mechanism are evaluated in fabricates micro components based on traditional turning operations such as straight turning and contouring of variety shapes to identify the machining capabilities and congeniality between the rotary axis mechanism and WEDM machine. Figure 3.1(a) and Figure 3.1(b) illustrate the overall flowchart of the research conducted.





Figure 3.1 (a): Flowchart of the research methodology



Figure 3.1 (b): Flowchart of the research methodology

The second stage gives regard to the parameter screening to obtain the suitable combination between machine electrical parameter, non-electrical parameter and rotary axis mechanism characteristics. The inappropriate parameter combination leads to wire breakage during machining and insufficient of discharge energy to erode the materials which conduced to no cutting process is performed. The parameter is rearranged several times to obtain the suitable combination of maximum and minimum of energy output. This method has the benefit to discover the machine limit to perform cutting process in any manner for next screening purpose.

In the last stage, the Taguchi experimental design practice is employed in obtaining the highly influence process parameter as well as minimizing the level range of parameter over the selected performance criteria. The screening process in this research work is purposely conducted to provide full details of the parameter optimization of WEDT process. Signal to Noise (S/N) ratio and ANOVA is occupied to analyse the significance of the variables. Only a few of the process parameters that possess statistical significant is selected for further optimization by using response surface methodology (RSM). The non-significant and less influenced process parameter remains fixed at the best level to maintain the low Ra value. The benefit of this method is that it is able to enhance the optimization result because the analysis now focuses on the most significant process parameter. Meanwhile, the range for each of the parameters is scaled down to obtain best fits mathematical model during parameter optimization.

The further optimization of process parameter for micro components fabrication by hybrid WEDT is performed by employing RSM technique which is Face-centred Central Composite Design (FCCD). A series of experimental works is carried out according to the FCCD design scheme and the details of the experimentation that possess materials and method is described later. A mathematical model is developed through ANOVA to indicate the relationship among parameter on Ra. The entire experimentation in this present study is focused in exploring the hybrid micro WEDT process parameter that influences the performance measures such as surface roughness and its integrity.

In the next step, the confirmatory experiment is conducted to distinguish the accuracy between the developed mathematical equation and the experimentation results. Finally, the optimization by employing desirability approach is conducted with goal to minimize the Ra value thus the predicted optimal parameters are established. The accuracy of the predicted optimal parameters is also verified by confirmatory experiment.

#### 3.2 Design and Construction of Rotary Axis Mechanism

In performing the turning process in WEDM, the conventional of WEDM machine has to integrate with working table that able to rotate the workpieces. Figure 3.2 illustrates the developed prototype architecture that suits to carry out of the turning process by WEDM.



Figure 3.2: Prototype architecture of the rotary axis mechanism

#### 3.2.1 Rotary Spindle and Housing

Rotary spindle is an important consideration because it is the main component in whole rotary axis mechanism especially shaft spindle and clamping system because it plays a part in manufacture precise in micro components. The selection of the inappropriate shaft spindle and clamping system may cause inaccuracy and out of the components tolerances. The main factor that contributes to the accuracy is run-out error. The selection and assembly of the clamping system should reduce and minimize the run-out error. In this present study, an in-house rotary axis mechanism is developed which consists of rotary spindle and housing and comprises eight components that work together to perform as WEDT rotary axis mechanism. Figure 3.3 shows the pre-assembly rotary spindle on a housing which shows each of the components placed. Figure 3.4 shows CAD model of the rotary spindle and cross-section of the housing which indicates the location of the radial oil seal and ceramic bearing in the housing.



Figure 3.3: Pre-assembly rotary spindle and housing (a) Front side (b) Back side



Figure 3.4: Radial oil seal and ceramic bearing placed in the housing

All the components selected are based on concept, theories and practices that has been used by the previous literatures. In addition, the components selected also are common parts which are commercialized in market except housing and housing cover. These components are easy to be replaced, especially for wear and tear component (carbon brush and ceramic bearing). Table 3.1 shows the details of the components which are used in developing this rotary spindle. Table 3.2 describes the function of each of the components to the rotary axis mechanism.

No.	Component	Dimension (mm)	Specification	Material
1	Straight Shank Collet Holder	20x100 (D x L)	Brand: Master Collet: ER16 Metric Clamp Diameter: 1-10 mm Run-out Tolerance: 15 μm (DIN6499B)	1065 Grade Carbon Steel
2	Housing	90x90x44.8 (W x L x T)	A pair of counterbored holes	Aluminium
3	Housing Cover	90x90x8.5 (W x L x T)	One counterbored holes	Aluminium
4	Carbon Brush Holder 🌿	59x59x14 (W x L x T)	<b>Spring Type:</b> Coil <b>Maximum Quantity:</b> 4 units carbon brushes	Copper and brass
5	Carbon Brush	12x21x8 (W x L x T)	Brand: Nippon, Japan	Graphite
6	Tooth Pulley	27x16 (D x L) Hub Diameter 26	Brand: RS Teeth: 48 Pitch: 2.5 mm	Aluminium
7	Radial Oil Seal	20x47x7 (ID x OD x T)	Including Garter Spring	Rubber
8	Ceramic Bearing	20x32x7 (ID x OD x T)	Brand: Kanzen Roulement, France Precision Levels: ISO 5/ ABEC 5 (ABMA, n.d.) Type: Deep Groove Radial Ball Bearing Closures: Double sealed Lubrication: Self Lubricated (Grease)	Races: 440C Stainless Steel Balls: Si <sub>3</sub> N <sub>4</sub> G5 diamond polished Seals: Rubber

Table 3.1: Name, dimension, specification details and material of the components

No.	Component	Function		
		• Work as spindle shaft in rotary axis mechanism		
		• Transmit power, torque and motion from one location to the		
1	Straight Shank	workpieces		
	Collet Holder	• Minimize the run-out error from the joining between shaft and		
		chuck or others clamping devices (Janardhan and Samuel,		
		2010).		
2	Housing	Locates a pair ceramic bearing at centre of the housing for		
2	Tiousing	holding the spindle shaft		
3	Housing Cover	Place a radial oil seal		
4	Carbon Brush	Hold and maintain constant contact forces on carbon brushes to		
-	Holder	spindle shaft (Janardhan and Samuel, 2010)		
5	Carbon Brush	Deliver or collect electrical current from a rotating to static		
5		components, or vice versa (Qu et al. 2002a)		
	11.1	• Receives motion from timing belt which is transmitted by		
6	Tooth Pulley and	another pulley and driven by electrical motor (Sun et al.		
	Tooth Belt	2017)		
	بيا ملاك	• Provide uniform flow of motions (Gohil and Puri, 2016)		
		• Seals around a rotating spindle shaft and housing from		
7	Radial Oil Seal	dielectric fluid and eroded particles (debris) that capable to		
,	Rudiul Oli Soul	enter the gaps around the bearing and assembled		
		components during EDM process (Parthiban et al. 2013)		
		• Support, ensure stability and provide frictionless rotation for		
8		spindle shaft		
		• Locate and hold a spindle shaft at centre of the housing		
	Ceramic Bearing	• Prevent the electrical discharge occurs between the gap on		
		steel bearing (Qu et al. 2002a)		
		• Prevent from back current that will damage the motor		
		(Janardhan and Samuel, 2010)		

Table 3.2: Components and their functions in rotary axis mechanism

Additionally, housing is fabricated by CNC Mill assisted with computer-aidedmanufacturing (CAM) to obtain equal plane between machine table and straight shank collet holder. The function of this housing is to locate a straight shank collet holder which functions as a clamping device. Aluminium has been selected as material for housing and its cover due to its excellence in electrical conductivity for grounding between machine table and resistance to the corrosion when the housing is exposed to dielectric fluid and eroded particles (debris) during EDM process.

#### **3.2.2** Base Frame and Motor Bracket

The idea proposed to this design is in the manner of benefits to the machine operators. All the rotary axis mechanism components are assembled to the base frame to purposely ease mounted and de-mounted on the WEDM machine worktable with minimum alignment procedure. For that reason, the non-integrated base frame design and motor bracket is introduced.

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#### **3.2.2.1** Design Base Frame and Motor Bracket

As shown in Figure 3.5, a base frame with dimension 178 x 210 x 25 mm that is made by 25 x 25 x 3 mm stainless steel AISI 304 angle bars. The purpose of this base frame is to locate the rotary axis mechanism as well as merging between DC motor and the sets of housing. This design of base frame allows the direct contact of aluminium housing to the machine worktable in providing sufficient current density to well performed the erosion process. At the Section A in Figure 3.5, this section is cutting by WEDM process to produce perpendicular plane by referring to the flatness of machine table. This technique is able to minimize the uncertainty of straight cylindrical shaft during machining. The DC motor is also located in this base frame with availability of tension bolt in controlling the tension of the tooth belt to work well during operating.



Figure 3.5: The fabricated rotary axis mechanism base frame

Figure 3.6 shows the finished fabricated parts of plastic insulator and motor bracket that is used in this present study. The plastic insulator is proposed to prevent the back current to the DC motor by striking of energy between WEDM machine worktable and the DC motor itself. The aluminium of motor bracket is a customized design and fabricated because none of the commercialized motor mount heatsink suits for this application as well as for the specific type DC motor. The primary function of this motor mount is to isolate the DC motor from shaking going on as energized. By adding a little fabrication process, the fins that function as heatsink have already made for precaution step design. The poor heat dissipation in the motor has the potential to reduce the motor life expectancy. The plastic insulator is fabricated by conventional milling machine. Motor mount heatsink is fabricated by WEDM and milling process. During fabrication process, both of the parts consist of slitting, slotting and drilling operations. The illustration about assembly of rotary spindle, motor, motor bracket and base frame have been attached in Appendix A.



Figure 3.6: Completed DC motor with set of motor mount heatsink and its insulator

## 3.2.3 Speed Controller

In the development of speed controller, the idea is to employ the pulse-widthuniversity technical matter matter and the pulse-width modulation (PWM) method in benefits of variable duty factors that suitable for speed controller application; in this case, the rotational spindle speed in the rotary axis mechanism. Therefore, all of the electronic parts that are used in this research study are based on the development of speed controller system by PWM technique.

# 3.2.3.1 Design and Develop of Speed Controller

Most of the electronic parts are supplied by Cytron Technologies Sdn. Bhd. Malaysia except the DC motor. Figure 3.7 shows the connection between electronic components consist of microcontroller board, motor driver and voltage regulator. According to the Figure

3.7, the input power source for whole system is a 24V power supply with 1 ampere. However, only the brushed DC motor are energized by 24V, other components are operated less than 12V. Therefore, the voltage supplied is reduced to 12V by voltage regulator to energize microcontroller board (SK40C). All the components are connected as illustrated in Figure 3.7. MD10C is preferred to drive the DC motor because it offers both lockedantiphase and sign-magnitude PWM signal. Other than that, this motor driver supports wide range of voltage that suits the particular motor in this research work. More precisely, the motor driver has four inputs and two output pins with one grounding pin. The first two input pins are connected to the power supply and the two output pins are connected to the DC motor. The other two input pins are the PWM pin and the direction pin. These pins with one grounding pin are connected to the SK40C and they control the amount and direction of the current that goes into the DC motor. Table 3.3 describes each of the electronic components and their functions.

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Electronic	Descriptions/Functions	
Components		
	The main purpose of the microcontroller board is to interface and	
	response with the sensors and devices by manual input. SK40C only	
Migropontrollor	required 12V power supply to switch on. Therefore, the step down	
board (SK40C)	voltage regulator (24V to 12V) is used. This research work utilizes	
board (SK40C)	only few of pin connection to integrate with SK40C board. There is	
	LED indicator used to show whether the input signal from push	
	button is received and transfer the logic to the MD10C.	

PIC16F887	In this research works, the microchip PIC16F family type is used namely PIC16F887 and it works well with SK40C. The basic operation is that the PIC will process the inputs from push buttons and outputs will be sent to driver motor system circuit for motor control operation
Liquid Caustal	Attached to SVAOC to indicate the status of the system during
	Attached to SK40C to indicate the status of the system during
Display (LCD)	operating.
	MD10C is designed to drive high current brushed DC motor up to
Motor Driver	13A continuously. Speed control PWM frequency up to 20KHz.
(MD10C)	Input voltage 5 to 25V.
Capacitor and	To decrease the voltages and provide the exact value of the output
Voltage	in DC voltages. The L7812 is a positive voltage regulator that
Regulator produces a voltage of 12V.	
Duch Dutter	A simple switch mechanism for controlling a process; in this case,
	to turn on the SK40C and reset the whole system.
LISB DIC	It is a USB (Universal Serial Bus) based ICSP (In Circuit Serial
	Programming) programmer. It allows users to program their hex
Programmer	code into the microcontroller by using commonplace USB
(UIC00B)	into the interocontroller by using commonplace ODD
112	connection.

# 3.2.3.2 Program PIC Microcontroller AL MALAYSIA MELAKA

Programmed is the last stage after development of the hardware and before testing the system. In this study, the program writes into PIC microcontroller which is the brain to drive the motor with specific rotational speed. Figure 3.8 shows the example of the coding in MPLAB to drive the rotary axis mechanism by PWM method, the further details of coding is described in Appendix B. The programmed is improvised from Cytron Technologies tutorial module (Cytron Technologies, 2011) for SK40C in drives DC motor by MD10C. In this project, MPLAB IDE V8.60 compiler is used to write and compile the program code for PIC16F887, while UIC00B Programmer is used to write the hex file generated into PIC16F887 through PIC Kit 2 software. UIC00B Programmer (Figure 3.9) is the interface between computer and the SK40C microcontroller.



Figure 3.8: The example of the coding that is used in this research study



Figure 3.9: UIC00B Programmer

## 3.2.4 Final Assembly

In the final assembly, all the parts are installed together as shown in Figure 3.10 to Figure 3.12. The set of DC motor is mounted to the base frame as mentioned in previous section. Then, the complete pre-assembly set of housing is also mounted to the base frame.

After that, the tooth belts are fitted on tooth pulleys at the DC motor and shaft spindle. The tension bolt is used to obtain suitable tension on the tooth belt. Tooth pulleys and belt are used to simply transfer the rotational motion from the powered pulley on a DC motor to one driven pulley at spindle shaft. The straight shank collet holder is used with the ER16M adapter as clamping devices and serves as a spindle shaft. The range diameter that is allowed for this adapter is 1 to 10 mm. In this present study, the range adapter of diameter size about 9 mm.

Spindle shaft is placed on a pair of ceramic bearings at both end, and the ceramic bearing is press fitted to the housing. The ceramic bearings are deep groove Si<sub>3</sub>N<sub>4</sub> ball bearings with stainless steel inner and outer races, rubber sealed with ABEC grade 5 is used to prevent the electrical discharge to occur between the gaps on ball bearing. At the outer of the housing, radial oil seal is placed to avoid the excess melted material (debris) during erosion process as well as de-ionized water from entering the bearing races. Since the EDM process requires connectivity between terminals, the rotating workpieces require link to the WEDM machine worktable. Therefore, a pair of carbon brush is a slid contact to the spindle shaft and the carbon brush is connected to the housing which has direct contact to the WEDM machine worktable. Carbon brushes are used to transmit electrical current from a static to a rotating spindle shaft. It is fixed on the back of the housing by using the carbon brush holder. The workpiece is clamped on the spindle shaft by collet adapter and locked by collet nut. In this present study, the rotation direction of the spindle shaft is designed similar to the DC motor direction with same amount of ratio. Finally, the rotary axis mechanism is mounted to the WEDM machine worktable aligned with X or Y axis.

The speed controller is energized by plug-in the 24V adapter as power supply cable to the female jack and turn the switch on. Then, the connection cable is inserted to the female jack that link to motor driver (MD10C). The details of the speed controller as shown in Figure 3.13 and Figure 3.14 show the female jack for power supply, motor driver and the USB port. During spark erosion by hybrid micro WEDT, the rotating workpiece is interfered by continuous perpendicular electrode wire that is replenished to replace the new electrode wire surface that is available for next spark. By applying the rotational motion, the unmachined portion of the workpiece surface is replaced by machined portion, and vice versa.



Figure 3.10: CAD design of final assembly of rotary axis mechanism for hybrid micro WEDT



Figure 3.11: The actual final assembly of rotary axis mechanism for hybrid micro WEDT



Figure 3.12: The actual final assembly of rotary axis mechanism for hybrid micro WEDT



Figure 3.13: The final assembly of speed controller



Figure 3.14: Rear side of speed controller

# 3.3 Hybrid Micro WEDT Experimental

## 3.3.1 Research Material: Ti6Al4V

The Ti6Al4V rod with diameter of 9.49 mm is being used as the workpiece materials for the present experiment. This material has been purchased at E Steel Sdn. Bhd. Malaysia. The details of the fabrication, physical and mechanical properties have been attached in Appendix D. Table 3.4 specifies the general specification of the Ti6Al4V that is being used for cylindrical micro turning by hybrid WEDT in this study. The preparation that has been done before specimen goes to the machining stage is that it has been cut to 20 mm in length by WEDM machine. Then, it is being immersed by using ultrasonic bath (Figure 3.15) to remove the debris and other contaminant containing on the surface of materials. Thereafter, the specimens are being dried at room temperature before being weighed to obtain the mass for each of the specimens. Table 3.5 shows the specimens cleaning details by ultrasonic bath.

Table 3.4: The specifications of Ti6Al4V (E Steel SDN. BHD., n.d.)

Diameter (mm)	Density (g/cm <sup>3</sup> )	Hardness Rockwell C	Elastic Modulus (GPa)
9.49	4.42	36	114

Table 3.5: The ultrasonic bath parameter during specimens cleaning preparation

2		
Brand	Jeio Tech	
Run Time (min)	15	
Frequency Level	Max	
Temperature ( <sup>o</sup> C)	27	
Cleaning solution	Ethanol 95% Denatured	
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Figure 3.15: The specimens is being immersed and cleaned by ultrasonic bath method

#### **3.3.2 Electrode Material: Brass**

The selected material for the electrode wire is brass with a diameter of 0.25 mm which has been bought at EDM Tools Sdn. Bhd. Malaysia (Figure 3.16). This type of electrode wire is known to have the advantage of delivering additional usable energy to the machining zone as well as cooling the electrode wire because the zinc in the composition of brass is easily vaporized. Table 3.6 illustrates the properties of electrode wire. Hard wire is referred as the ability of electrode wire to resist breakage and deflection because of its nature in high tensile strength and retain straighter.



Table 3.6: Wire electrodes properties (EDM Tools, n.d.)

Figure 3.16: 0.25 mm of brass electrode wire that is being used in this research work

#### 3.3.3 Wire EDM Machine

The experimental work in this study is carried out by a WEDM machine modelled Mitsubishi RA90. This machine is non-submersible and utilizes de-ionized water to flush away the debris while machining happens in the machining gap. The jet is shot from upper and lower nozzles at specific distance.

Mitsubishi RA90 WEDM machine possesses the setting unit for axes X, Y, U and V of 1  $\mu$ m, the feed driving unit is 0.05  $\mu$ m, and the positioning error for the minimum deviation is 0.001, while the feed motion is driven by machine table that is being controlled by servo mechanism. The resistivity of the dielectric fluid is 6 x 10<sup>4</sup>  $\Omega$ cm. The machine is being energized by a transistor-type pulse generator. Maximum machining gap current is as much as 50 amperes. Figure 3.17 shows the Mitsubishi RA90 WEDM machine that is being used for the whole experiment and is located at Mould and Die Laboratory in Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka.

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Figure 3.17: Mitsubishi brand of the WEDM machine specific model RA90

## 3.3.3.1 Parameter

According to the Mitsubishi RA90 machine parameter library and machining characteristics handbook (Mitsubishi-Electric-Corporation, n.d.), this machine has unique feature that is specific for industrial purpose where this machine utilizes parameter library that represents the actual parameter unit which known as 'Notch' except for voltage gap, wire tension and pre-tension. Moreover, the parameter conditions for this machine are grouped only to four categories namely Aluminium, Copper, Tungsten Carbide and Steel. The purpose of the provided parameter conditions is only for common type of materials in general cutting applications and it is based on thermal and electrical properties of the materials. Each of the material categories is being grouped to three types of power supply which are Power Supply 1 known with the term 'HP' which is used for rough machining, Power Supply 2

known with the term 'HP/MP' used for medium finish and Power Supply 3 known as 'LA' used for obtaining good surface finish. Table 3.7 describes the details of each parameter that is used by Mitsubishi RA90.

Damanadama	Value	Descriptions		
Parameters	(Units)			
Voltage	1-16	This switch sets the height of the gap voltage during no-load.		
open, Vo	Notch	Voltage increases for larger notch number.		
		This switch sets the size of the peak current that flows the gap.		
Intensity of	1-18	• HP: rough machining power supply mode. Notches: 4 to 16		
Pulse, IP	Notch	• MP: medium finish power supply mode. Notches: 4 to 18		
ŝ	, The second sec	• LA: finish machining power supply. Notches: 1 to 3		
TEK		Switch to set the time between end of discharge and new voltage		
Off Time	1 16	applied. The OFF notch does not need to be set if IP is set to		
OII TIME,	I-IU Notah	notch 4 or higher. Off time decreases for lower stages and		
OFF	Noten	machining speed increases proportionately. However,		
5	يا ملا	machining is not stable, causing wire breakage or short circuits.		
	UNEDO	This switch determines the machining stability and is used to		
U Stabilizar	1-8 Notch	finely adjust the current. The higher the value is, the faster the		
		machining speed will be. However, if too high, wire breaks will		
А, 5А		occur. Thus, set this according to wire diameter where the		
		smaller notch value for the smaller wire diameter.		
		This switch determines the machining stability, and is used to		
Stabilizer B,	1-16	finely adjust the off time. The higher the value, the slower the		
SB	Notch	machining speed. This parameter must be set according to the		
		material of the workpiece.		
		This switch is used to stabilize machining for the finishing		
Stabilizer	1-3	<ul> <li>circuit. The higher the value makes the machining more stable.</li> <li>However, the result of surface roughness value will increase.</li> <li>When IP ≥4 notches, SC only able set to 1.</li> </ul>		
C, SC	Notch			

Table 3.7: Mitsubishi RA90 parameters and their descriptions (Mitsubishi-Electric-Corporation, n.d.)

		This switch sets the machining stability, and is used particularly	
Stabilizer E,	1-5	for first cut machining. Notch 1 is to turn off, and notches 2 to 5	
SE	Notch	are to turn on. As the notch value increases, the machining	
		becomes slower but wire is difficult to break.	
Voltage	1-150	This switch sets the average machining voltage used as a target	
Gap, VG	Volts	value when machining with optimum feed.	
Wire Speed,	1-16	This switch sets the wire feedrate. The higher the value, the	
WS	Notch	faster the wire feedrate.	
Wire	1 5 25	This switch sets the wire tension. The higher the value, the	
Tension,	4.5-25	This switch sets the wife tension. The higher the value, the	
WT	Newton	higher the tension of wire.	
Pre-	0.4-2.4	This switch sets the wire pre-tension. The higher the value, the	
Tension, PT	Newton	higher the pre-tension of wire.	
Liquid	12	This switch sets the dialectric fluid flow rate. The flow rate is	
Quantity,	1-2 N. ( 1	This switch sets the delectric fluid now fate. The now fate is	
LQ	Noten	weak when set to 1 and strong when set to 2.	
Liquid	1.0	This switch sets the specific resistivity of the dielectric fluid.	
Resistivity,	Notel	The higher the value, the lower specific resistivity. 1 indicates	
LR 🎍	Noten	that the pump is always ON.	
	-		

# 3.3.3.2 Pulse Waveforms Characteristics – MALAYSIA MELAKA

Typically, every type of pulses in WEDM contributes to the energy that is produced per unit time at every single discharge during erosion process. The higher the energy spent, the wider craters formed. However, the fundamental pulse waveform in WEDM is unfit for Mitsubishi RA90 machine. Therefore, Figure 3.18 explains the further details about function and contribution for each of the parameters to produce the energy in voltage graph and current graph. Figure 3.18 only illustrated the pulse waveform to summarise details of each parameters and it functions as described in Table 3.7. The information about pulse waveforms characteristics for Mitsubishi RA90 is crucial in this study because the formation of arc and its region is highly occurred in WEDT compared to WEDM. The advantage of this machine is that the arc and short pulse are able to be controlled by parameter term stabilizer A and stabilizer B. Furthermore, if the intensity of pulse is set above than 4 Notch, the pulse off time become auto tuned.



Figure 3.18: Mitsubishi RA90 pulse characteristics (Mitsubishi-Electric-Corporation, n.d.)

# 3.3.4 Experimental Setup

An in-house rotary axis mechanism is being used to machine cylindrical workpieces in WEDM. The experimental setup is shown in Figure 3.19 and Figure 3.20 which includes the configuration of the rotary axis mechanism that is placed on the Mitsubishi RA90 machine table to rotate Ti6Al4V specimens in X-axis during machining process. Table 3.8 indicates the step-by-step procedure for machining preparation that has been carried out in this study. Every single wire positioning motion and measurement, 0.005 is specified as the value of the error deviation. In addition, the measurement is made by built-in machine capacitance system while spindle rotates in slow motion at approximately < 5 rev/min. In addition, the repetitions of the positioning occur five times.



Figure 3.19: The position of rotary axis mechanism on WEDM machine table



Figure 3.20: The details configuration of rotary axis mechanism to the WEDM machine including clamped workpiece and position of electrode wire

Table 3.8: The details procedure of installing the workpiece, zero-positioning electrode
wire and the approach of control radial depth of cut

Step	Figure	Descriptions
1	Collet Holder Specimen	Specimen is clamped on the ER16M collet as clamping devices with overhang as much 10 mm. The overhang is measured at distance of the specimen extend from the end of collet holder.
2	Move to X direction Move to Y direction	With arrangement of wire positioning error is 0.005, the electrode wire then is positioned to the X plane of the collet holder to form pilot X reference plane (zero).
3	UNIVERSITI TEKNIKAL MALA	Thereafter, the electrode wire is positioned towards the specimens in order to form reference plane (zero) for Y axis.
4		Afterwards, the electrode wire is positioned towards the centre of the radial specimens in order to form real X reference plane (zero).



Finally, to obtain the final diameter of the machining parts is by controlling the value of the radial depth of cut. In this present study, the final diameter that has been specified is 0.8 mm. However, the value depth of cut is not constant because of the variation during measurement.

The selection of 0.8 mm as the final diameter as to prevent the possibility for the machined parts to burn or bent by thermal stresses due to the high energy density during machining.

# 3.3.5 Machining Strategies

The straight turning machining strategy is being employed with a single pass approach along a machining length of 4 mm. In straight turning, the material is removed in the longitudinal direction with a constant diameter over the length to produce a cylindrical surface or straight shaft by the positioning of the depth of cut value. Straight turning, in reference to traditional processes like micro-turning, usually consists of a multi-layered cutting when a large amount of material is to be removed, such as several rough cuts followed by a finishing cut. In hybrid micro WEDT, the multi-layered cutting can be eliminated by a single pass machining approach. Figure 3.21 shows the straight turning with a single pass machining path programmed by computer numerical control (CNC) using the G-code on the symmetrical, cylindrical-shaped workpiece.



Figure 3.21: Straight turning program with single pass path condition

#### **3.3.6** Performance Criteria Evaluation Method

# **3.3.6.1** Arithmetic Average Surface Roughness (Ra)

In this present study, the micro-cylindrical shape machined parts that has been machined by WEDT are scanned by optical profilometer Alicona Infinite Focus Microscope (IFM) G4 (Figure 3.22). The scanned area of XY is about 2.7088 mm x 5.66.01  $\mu$ m with sampling distance of 459.43 nm x 459.43 nm. Vertical and lateral resolution is 26 nm and 3.67  $\mu$ m respectively.

The high resolution digital 3D image of the cylindrical surface is formed as shown in Figure 3.23. The Ra values are determined from the 3D image by refereed ISO 11562-Gaussian Profile Filter for surface analysis (International Standard Organization, 1996a), ISO 4288- conditions for roughness measurements (International Standard Organization, 1996b). The peaks and valleys are calculated with the profilometer's software Infinite Focus as illustrated in Figure 3.24. The arithmetic average surface roughness (Ra) is focused in this study. The reason to employ the non-contact surface roughness measurement is because the contact type measurement that uses stylus is unable to do well with voids or steep slopes as well as being limited by the size of the stylus tip. Take an example, if the stylus tip possesses too large of the curve radius, the resolution becomes poor. If the stylus tip radius is too small, the parts surface has potential to damage through ploughing.



Figure 3.22: Alicona Infinite Focus Microscope (IFM)


Figure 3.23: An optical image of machined surface of micro-cylindrical part by hybrid WEDT



Figure 3.24: The software Infinite Focus interface to measure the arithmetic average surface roughness

# **3.3.6.2** Weight Differences

The weight difference is used in this study to determine the quantity of attached debris on machine surface that is able to be removed during cleaning process. The weight of each of the specimens is obtained with the help of an analytical balance model AB135-S/FACT Dual Range Mettler Toledo (Figure 3.25) with readability of 0.01 mg.



Figure 3.25: Mettler Toledo analytical balances

# 3.3.6.3 Surface Morphologies

The microscopic study of the machined parts produced is measured by Scanning Electron Microscopy (SEM) EVO 50 model Carl Zeiss SMT, UK (Figure 3.26) to perform qualitative analyses of surfaces in those experiments described later. SEM being the most technique by the researchers in identifying the quality of surface integrity such as craters, macro-ridges and globules of debris. The microscopy graph in SEM principally produced a

two-dimensional plane, but as with cameras, the three-dimensional plane is able to be generated by tilting the specimens. Before the analysis begin by SEM, the specimens are cleaned by ethanol cleaning solutions for free from non-conductive contaminant and debris. Then, the specimens are directly placed to the machine stage that is located in vacuum chamber. The magnification is set in the range of 50x, 100x, 250x, and 500x to view the microstructure more clearly.



Figure 3.26: Scanning Electron Microscope (Model EVO 50 United Kingdom)

# **3.4** Selection of Process Parameter (Screening)

# 3.4.1 Method in Selection Range of Parameter for Machining Capability

In this research works, to investigate the influences of the parameters and then to carry out the optimization for surface roughness, it is necessary for WEDM machine has capability to perform the cutting process for the cylindrical workpiece of Ti6Al4V. However, due to the characteristics of Ti6Al4V that possess low thermal conductivity and high chemical reactivity properties that cause wire breakage as well the unstable pulse waveform hybrid micro WEDT operations during machining, lots of obstacles has been encountered only when to perform cutting process. The screening of the process parameter is required and it begins by selection of the range parameter with suitable combination. The consideration of the initial screening is to ensure that all the parameters work properly to perform cutting process. An alternative approach has been used when there is constraint with the current experiment strategies. Table 3.9 explained type of design of experiment strategies with their own limitations that are used in this research study.

1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	7	
Design of Experiment Strategies	Number of Trials	Limitations
ملیسیا ملاک Full Factorial SITIT	يني ٽيڪنيڪل KNIKAl <sub>2048</sub> ALAYSIA	When the combinations among the parameters levels unable to performs the cutting process, new full factorial design scheme necessity to recreated, Therefore, the number of trials increased abundantly
Fractional Factorial higher resolution	128	No combination each of the levels among the
Taguchi Orthogonal Array	Less than 64	parameters example in
Plackett-Burman	12	Figure 3.27. Therefore, the occurrence of wire breakage and insufficient discharge energy likely to occurred.

Table 3.9: Design of experiment strategies comparison

Full I	Factorial Ex	perim	ent	
	Variation	А	В	С
Factor A	1	+1	+1	+1
Factor B	2	+1	+1	-1
Factor C	3	+1	-1	+1
	4	+1	-1	-1
	5	-1	+1	+1
	6	-1	+1	-1
	7	-1	-1	+1
	8	-1	-1	-1

Figure 3.27: The comparison between full factorial and fractional factorial in design of experiment strategies

Eventually, rearrangement approach is used to ensure there are no occurrence of wire breakage or insufficient electric sparks to erode that led the machine to stop suddenly. Figure 3.28 indicates the types of errors that occur when the machine stops resulting to the cutting process from being performed. This method is about to push the machine limit to perform cutting process in any manner for screening purpose since the cutting process employs electrical discharge sparking phenomenon which is known as stochastic process.

T210 WIRE BREAKAGE 0210 12:37	T211-30 SEC CONTACT 0211 11:17 AR
	MAL AVSIA MELAKA
L 5 N 30 B 0 PROGRAM G54 X -0.459 Y 0.000 U 0.000 V 0.000 RM 10.041	L 5 N 30 B 0   PROGRAM G54 -0.601 -0.000 <t< td=""></t<>
N30 G92 X0.0 Y0.0 N30 G01 X-10.5 M30 %	N30 G92 X0.0 Y0.0 N30 G01 X-10.5 M30
(a)	(b)

Figure 3.28: The type of machine error if encountered a) Wire breakage b) Insufficient sparked energy

The selection of the levels begins by performing the pilot experimental works. Among four of the general parameters as indicated in sections 3.3.3.1, only parameter conditions for Tungsten Carbide is capable to perform the cutting process for the Ti6Al4V without occurrence of wire breakage or insufficient electric sparks like the other three parameter conditions which are Aluminium, Copper and Steel. Then, the parameters that works well in machining the rod of Ti6Al4V has been expanded by rearranged method. Table 3.10 shows the parameter conditions for Tungsten Carbide that used the initial screening process parameters for Ti6Al4V. The rearranged results are covered in section 4.3.1 in chapter 4. The levels of the parameter are rearranged according to machining characteristics handbook (Mitsubishi-Electric-Corporation, n.d.) in controlling the sufficient electric sparks and occurrence of wire breakage as mentioned in Table 3.7. For example: as the notch value increases for stabilizer E, the machining becomes slower but wire is difficult to break.

Table 3.10:	Parameter condit	ions for Tungste	n Carb	ide (Mitsu	ıbishi-I	Electric-(	Corporation,
		n.d	.)	1.0			
	<b>UNIVERSITI</b>	TEKNIKAL	MAI	AYSIA	MEL	ΔΚΔ	

Tungsten Carbide											
Туре: НР 2211 (Н2	229)	Levels									
Voltage Open	Notch	16									
Intensity of Pulse	Notch	6									
Stabilizer A	Notch	1									
Stabilizer B	Notch	4									
Stabilizer E	Notch	9									
Voltage Gap	volt	42									
Wire Speed	Notch	12									
Wire Tension	Newton	13.5									

## **3.4.2** Taguchi Design Scheme (Orthogonal Array L<sub>12</sub>)

The objective of the parameter screening that is being employed in this study is to obtain the highly influenced operating conditions to the Ra for comprehensive parameter investigation and optimization by using RSM. Therefore, the outcome of this screening process should contribute to providing small number of parameter for optimization by RSM. Apart from that, the range for each of the parameters is scaled down to obtain best fits mathematical model. Meanwhile, the other parameter that is not selected remains fixed at the best level in order to produce low Ra value. Figure 3.29 illustrates the flow of the process for the parameter screening by Taguchi OA.





Figure 3.29: The parameter screening process flowchart

In this study, Taguchi  $L_{12}$  orthogonal array (2<sup>11</sup>) is being used as the experimental design for the screening purpose to establish the optimum operating conditions by means of S/N ratio analysis and to estimate the contribution of individual parameters using ANOVA, to screen the most important process parameter in hybrid micro WEDT towards the Ra. Taguchi OA  $L_{12}$  is suggested by Roy (2001), up to 11 parameters with 12 number of experimental run. Moreover, this design is only capable to investigate the influences of the main effects only. Additionally, the purpose of this screening process is to establish

comprehensive parameter optimization in fabrication of micro-cylindrical components at the end of this study. Table 3.11 shows the orthogonal array for  $L_{12}$  of Taguchi method that is being employed in this present study.

Experiment					Colu	ımn/Fa	actor				
Number	Α	В	С	D	E	F	G	Η	Ι	J	Κ
1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	2	2	2	2	2	2
3	1	1	2	2	2	1	1	1	2	2	2
4	1	2	1	2	2	1	2	2	1	1	2
5	1	2	2	1	2	2	1	2	1	2	1
6	1	2	2	2	1	2	2	1	2	1	1
7	2	1	2	2	1	1	2	2	1	2	1
8	2	14	2	1	2	2	2	1	1	1	2
9	2	1	1	-2	2	2	1	2	-2	1	1
10	2	2	2	1	1	1	1	2	2	1	2
11 -	2	2	1	2	1	2	1	1	1	2	2
12	2	2	1	1	2	1	2	1	2	2	1
A, B, C	C, D, E	, <i>F</i> , <i>G</i> ,	H, I, J	I and K	X = Fa	ctor	1 an	d 2 =	Level		

Table 3.11:  $L_{12}$  orthogonal array for eleven factors and two levels (2<sup>11</sup>)

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There are 11 process parameters that are selected according to the machine capability

itself in terms of electrical parameter, non-electrical parameter and rotary axis mechanism characteristic. The parameters that are selected for this screening process namely voltage open (Vo), intensity of pulse (IP), stabilizer A (SA), stabilizer B (SB), stabilizer E (SE), voltage gap (VG), wire speed (WS), wire tension (WT), rotational spindle speed (RSS), feedrate (FR) and spindle direction (SD). Every single parameter is divided into two levels which are 1 and 2 as indicated on Table 3.12 and analysed by Minitab 17 of statistical software. The experimental run is conducted randomly according to Taguchi OA design scheme to reduce biasness. Then, the raw data is recorded for each of the trial conditions as well as S/N ratios of the repeated data points.

Doromotor	Unit	Notation	Level			
I al allietel	Umt	NUTATION	1	2		
Voltage Open	Notch	Vo	6	8		
Intensity of Pulse	Notch	IP	8	10		
Stabilizer A	Notch	SA	1	3		
Stabilizer B	Notch	SB	6	12		
Stabilizer E	Notch	SE	2	5		
Voltage Gap	volt	VG	40	140		
Wire Speed	Notch	WS	10	16		
Wire Tension	Newton	WT	10.6	14.8		
Rotational Spindle Speed	rev/min	RSS	50	2400		
Table Feedrate	mm/min	FR	0.05	0.1		
Spindle Direction	-	SD	Upward	Downward		

Table 3.12: 11 assigned design variables, units, notations and levels for Taguchi OA L<sub>12</sub>

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Minitab 17 of the statistical software is used for analysing data to generate outputs like design scheme, plots of S/N responses graphs, parameters ranked and contributions as well as ANOVA for S/N data. In this screening stage, the lower value of Ra is the priority. Therefore, "the small better" formula is applied to calculate the S/N ratio of Ra. The higher S/N ratio is required to achieve stable quality. In this present study, the desired objective is to obtain optimal value the smaller the better in the Ra. 12 experiments have been conducted using Taguchi experimental design method and there are two replicates for each experiment to obtain S/N values.

# 3.5 Machining with Highly Influences WEDT Process Parameters

The high influence of the level, range and process parameter of hybrid micro WEDT from the screening result is used to fulfil the experimental design scheme in developing comprehensive hybrid micro WEDT process parameter optimization. The last stage in this research work is machining with highly influenced hybrid micro WEDT process parameter by employing RSM specific to FCCD.

# 3.5.1 RSM: Face-centred Central Composite Design Scheme

In the present study, the experiments are designed according to the Face-centred Central Composite Design (FCCD) technique. This design consists of a centre point, four factorial points and four axial points or also called as star points which have a distance  $\alpha$  (alpha) from its centre (Figure 3.30). FCCD itself yields high flexibility and efficiency in producing the overall experimental error in less number of the experimental run. The experimental design has been developed on the basis of four numeric input factor. Each one of the numeric factors has two levels. If four of the factors (k) are selected in this stage, the FCCD design scheme which has an alpha value is one in this experiment consisting of 16 factorial design corner points (2<sup>k</sup>), eight axis star points (2×k) and six centre points at zero levels for estimating pure error (k is the number of parameters=4). The design is generated and analysed using Design-Expert software 7.



Figure 3.30: Face-centred Central Composite Design (Whitcomb and Anderson, 2004)

This design is employed when there are difficulties to hit the specified levels by employing CCD technique (Whitcomb and Anderson, 2004). In this research work, the Box Behnken technique is conducted at first for parameter optimization purpose. However, there is none statistical significant model that is produced. Several countermeasures are performed to obtain statistical significant model but still no statistical significant model is found. This circumstance might be due to the process variation of hybrid micro WEDT that is known as stochastic process. Therefore, the further parameter optimization in this research work is done by the procedure that is suggested by Whitcomb and Anderson (2004). They suggested FCCD; the experimentation is started by the conducting the full factorial at beginning (example: 16 run) that only fits for two-factor interaction (2FI's). It is followed by conducting the sixth centre points (default) to uncover the curvature of response surface. If there is curvature on data measured at centre points, it means that the experimental result reaches the operating regions. Lastly, the additional of eight star points experimental is conducted to estimate the response curve. By employing this procedure, positive result is obtained. Table 3.13 shows the example of coded values for 30 run of experiments that are generated by using four factors and two levels of FCCD technique.

·						
		Standard	A:	B:	C:	D:
		Order	Parameter	Parameter	Parameter	Parameter
		Order	1	2	3	4
		1	-1	-1	-1	-1
		2	1	-1	-1	-1
		3	-1	1	-1	-1
		4	1	1	-1	-1
		5	-1	-1	1	-1
Block		6	1	-1	1	-1
		7	-1	1	1	-1
	Full	8	1	1	1	-1
1	Factorial	9	-1	-1	-1	1
		10	1	-1	-1	1
		11	-1	1	-1	1
	MAL	12	1	1	-1	1
	E.	13 🦕	-1	-1	1	1
	NN.	14 Ş	1	-1	1	1
	F	15	-1	1	1	1
	E	16	1	1	1	1
	No.	23	-1	0	0	0
	in the second	24	1	0	0	0
	Star Points	25	0.*	a. 1 "	0.0	0
	(Estimation	26	0	. 12.	0-	0
	of Response	ei-27-ck		AL AVOCIA		0
	Surface)	28	0	0	1	0
Block		29	0	0	0	-1
2		30	0	0	0	1
	_	17	0	0	0	0
	Centre Point	18	0	0	0	0
	(Estimation	19	0	0	0	0
	of	20	0	0	0	0
	Curvature)	21	0	0	0	0
		22	0	0	0	0

Table 3.13: Face-centred central composite design (FCCD) used in this research study for k=4

# 3.5.2 Validation of the Process Model

Besides generating parameter optimization in hybrid micro WEDT, the RSM method also produces mathematical modelling equation that represents relationship between process input parameters and the response. The accuracy of the mathematical equation is evaluated by the confirmatory experiments through the residual error. The confirmatory experiment is performed by selection of new combination of the process parameter that is not listed or generated by FCCD design scheme. By employing the suggested mathematical equation that is generated according to design scheme, the residual error is compared between predictive and the experimentation result. The result value is calculated based on the percentage difference between experimentation run and predicted value over the predicted value. The value should be less than 10% to represent the accuracy of the model.

# 3.6 Summary

This chapter overall explains the methods, materials and setup of each of the experimentations to fulfil the research objective in optimization of hybrid WEDT parameter for micro-cylindrical components which consists of the development of rotary axis mechanism, hybrid micro WEDT parameter screening by Taguchi OA, optimization and validation by FCCD in the direction of the Ra as the evaluated response, and facilitated by microscopic examination.

#### **CHAPTER 4**

#### **RESULTS AND DISCUSSIONS**

## 4.1 Introduction

This chapter emphasizes the optimization of hybrid micro WEDT process parameter in micro- cylindrical machining. The contents are divided into four sections. The first section discusses about the evaluation of the complete rotary axis mechanism in fabricates micro components based on traditional turning operations such as straight turning and contouring of variety shapes. It also evaluated in terms of the achievable the rotational spindle speed and its dynamic run-out.

The second section consists of the initial parameter screening in obtaining the suitable combination between machine electrical parameter, non-electrical parameter and rotary axis mechanism characteristics. The inappropriate parameter combination leads to wire breakage during machining and insufficient of discharge energy to erode the materials which conduced to no cutting process is performed.

The third section discusses on the result of screening process with objective to provide small number and range of the parameter for optimization by response surface methodology (RSM). The screening process has revealed the effect of 11 parameters on arithmetic average surface roughness (Ra) that is identified through analysis of variance (ANOVA) by Taguchi signal-to-noise (S/N) ratio analysis for the smaller better characteristics. The further discussion about the exclusion of screening parameter for optimization purpose also has been covered to establish scientific understanding of this newly process.

The fourth section elaborates on the parameter optimization by using RSM analysis. Only four of the highly influenced parameters are selected from screening process to further investigated and optimized by RSM. A reduced quadratic model has been developed by ANOVA to predict the performance of the hybrid micro WEDT process focusing on Ra. Each of the parameters is being clarified of its possessions to the Ra including the interaction between them as it possesses significance in statistical analysis. The section ends by optimizing the hybrid micro WEDT parameter using the desirability approach. The confirmatory experiment is conducted to obtain the accuracy between the developed model and the actual experiment. The irregularities of eroded machined surface are characterized by topography measurement to provide the support information related to the hybrid micro WEDT machining nature.

# 4.2 Evaluation of the rotary axis mechanism

Subsequently finishing the final assembly for both rotary axis mechanism and speed controller, the integration for both of them is being evaluated. The first test is to obtain the range of rotational spindle speed. The allowable rotational spindle speed is 50 to 3000 rev/min which is being measured by Tachometer (Figure 4.1). In order to obtaining the bearing stability, the rotational of spindle was evaluated in terms of the dynamic run-out as indicated in Figure 4.2. The maximum run-out error was produced as much 9  $\mu$ m during the spindle rotates at 2100 rev/min and the less run-out error able to achieve when spindle rotates at 50 rev/min as much as 6  $\mu$ m. By increasing the spindle speed, the run-out has dramatically increases, but it was slightly decreases at maximum of spindle speed.



Figure 4.2: Results of the repeatable dynamic run-out of the spindle with varying rotational spindle speeds

Then, the performance rotary axis mechanism was evaluated for machining microcylindrical components. The designs that have been considered is straight turning with maximum achievable diameter followed by contouring turning with blending of macro and micro dimension. Table 4.1 shows the geometric and shape that is fabricated by this rotary axis mechanism assisted by WEDM machine and the macro-micrograph of the parts that is obtained through scanning electron microscope (SEM) as attached in Appendix C.

Table 4.1: Rotary axis mechanism fabrication capabilities of shape and design

Fabricated Components	Descriptions
UNIVERSITI TEKNIKAL MALA	Employs straight turning operation to form cylindrical shaft with maximum achievable diameter approximately 0.2 mm with machining length as much as 200 mm. The aspect ratio (Length/Diameter) as much 1000.
	Employs the operation of contouring turning to produce four types of shapes which are dovetail, cone, ellipse and groove. The micro size dovetail shape is successfully fabricated. More specifically, a bottom (neck) diameter of 163 µm and top diameter 372 µm.



Contouring turning and slitting operations of micro straight shaft and fins to the macro dimension of ellipse, cone and hour glass. Dimension of micro fins and straight shaft of 200  $\mu$ m and the average of slitting kerf width of 400  $\mu$ m.

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# 4.3 Experimental Screening Results

# 4.3.1 Selection of Process Parameter: Machining Capability

The initial parameter screening is performed to obtain the suitable combination between machine electrical parameter, non-electrical parameter and rotary axis mechanism characteristics. The consideration of the initial screening is to ensure that all the parameters work properly to perform cutting process. Results of the rearranged method showed in Table 4.2. Table 4.2 indicated all the parameters that work well (yellow colour) to perform cutting process without occurrence of wire breakage or insufficient electric sparks then further screened by Taguchi OA L<sub>12</sub>. To get better understanding of the approach for machining failure or success before employing Taguchi OA, the example can be shown by considering the following machining trials (summarized in Table 4.3). After that, the highly influenced parameter that contributes to the lowest surface finish is studied in advance for the purpose of comprehensive parameter optimization by using RSM.

Parameter	Unit		Level and Range														
Voltage Open	Notch	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Intensity of Pulse	Notch	4	15	6	7	8	9	10	11	12	13	14	15	16			
Stabilizer A	Notch	Ŧ	2	3	4	5	6	7	8								
Stabilizer B	Notch	HEK	2	3	4	5	6	7	8	9	10	11	12				
Stabilizer E	Notch	2	2	3	4	5						1					
Voltage Gap	volt	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	
Wire Speed	Notch	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Wire Tension	Newton	-5)	6	- 7	9	10	12	13	15	16	18	19	21	22	24	25	
Rotational Spindle Speed	rev/min	50	200	400	600	800	1000	1200	1400	1600	1800	2000	2200	2400	2600	2800	3000
Table Feedrate	mm/min	0.05	0.1	0.15	0.2												
Spindle Direction	-	Upward							Downward								

Table 4.2: The well combination among the parameters

\*Yellow Colour = Good Level and Range Combination

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Parameter	Unit	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
Voltage Open	Notch	7	8	8	5	6
Intensity of Pulse	Notch	9	10	7	8	8
Stabilizer A	Notch	2	2	2	5	3
Stabilizer B	Notch	9	6	9	2	12
Stabilizer E	Notch	3	5	9	2	2
Voltage Gap	volt	100	50	70	140	90
Wire Speed	Notch	13	16	13	10	15
Wire Tension	Newton	12	13	15	10	10
Rotational Spindle Speed	rev/min	1200	2400	1400	200	2000
Table Feedrate	mm/min	0.15	0.05	0.1	0.2	0.05
Spindle Direction	- Lundo	Upw	ard	ي هيچنې	Downward	
Resu		EKNIKAI	- MALA	YSIA MEL	.AKA	
Machining (	Operations	Failed	Success	Failed	Failed	Success
Rema	rks	Wire Breakage	-	Insufficient sparked energy	Insufficient sparked energy	-

Table 4.3: Summary of the example machining trials

# 4.3.2 Taguchi Orthogonal Array on Surface Roughness

This experimental work is conducted based on the Taguchi OA  $L_{12}$  for investigating the effects of process parameters on Ra. The selected process parameters are according to machine parameters and rotary axis mechanism characteristics. The Ra is being measured with Alicona Infinite Focus Microscope (IFM) instrument. The Ra and its S/N ratio value for every experiment data of each specimen is given in the tables for each section.

Table 4.4 and Table 4.5 show the results and the analysis of the S/N ratio for Ra. All the results were calculated through Equation 2.2 to Equation 2.14 in Chapter 2 by using software Minitab 17. Among all of the parameters, rotational spindle speed has large contribution to the Ra result as much as 28.34% followed by pulse intensity and wire tension as much as 24.18% and 20.57% respectively (Table 4.5). Compared to the other parameters, these three parameters contribute approximately 20% that indicating extraordinary influence of the Ra value in turning micro-cylindrical parts by using hybrid WEDT. According to Table 4.6, these three parameters are in top three ranking among the 11 parameters.

Furthermore, the results of the Ra also has quite high contribution from stabilizer E with 11.97% of contribution followed by voltage open, stabilizer B and spindle direction with percentage contribution as much as 7.44%, 3.05% and 2.9% respectively.

The other parameters are indicated as possessing less influence on the Ra where the percentage contribution is less than 1%. The parameters are wire speed, voltage gap, table feedrate and stabilizer A with percentage contribution as much as 0.65%, 0.51%, 0.34% and 0.064% respectively. Figure 4.3 illustrates the review of the percentage contribution in the pie chart for the effects of the operating conditions to the Ra value in turning micro-cylindrical parts by using hybrid WEDT.

Trial No	Voltage Open (Notch)	Intensity of Pulse (Notch)	Stabilizer A (Notch)	Stabilizer B (Notch)	Stabilizer E (Notch)	Voltage Gap (Notch)	Wire Speed (Notch)	Wire Tension (Newton)	Rotational Spindle Speed (rev/min)	Table Feedrate (mm/min)	Spindle Direction	Ra1 (µm)	Ra2 (µm)	S/N Ratio
1	6	10	3	12 YS	2	140	16	12.2	2400	0.05	Upward	6.57	6.39	-16.23
2	8	8	1	12	5	140	10	14.8	2400	0.05	Upward	3.89	4.16	-12.10
3	6	10	3	6	5 💈	140	10	14.8	50	0.1	Upward	6.02	6.09	-15.64
4	8	10	3	6	2	40	10	14.8	2400	0.05	Downward	4.84	5.17	-14.00
5	6	10	1	12	5	40	16	14.8	50	0.05	Downward	5.93	5.30	-15.00
6	6	8	3	12	5	40	10	12.2	2400	0.1	Downward	4.52	4.54	-13.12
7	8	8	3	12	2	40	16	14.8	50	0.1	Upward	5.06	5.14	-14.15
8	6	8	-72	6	2	140	16	14.8	2400	0.1	Downward	4.52	5.19	-13.75
9	8	8	-3	6	5	140	16	12.2	50	0.05	Downward	5.22	5.72	-14.77
10	8	10		12	2	140	10	12.2	50	0.1	Downward	6.52	6.35	-16.17
11	6	8	1	6	2	40	10	12.2	50	0.05	Upward	6.86	6.43	-16.46
12	8	10	1	6	5	40	16	12.2	2400	0.1	Upward	5.55	5.48	-14.83

Table 4.4: Experimental results

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Parameter	Stdized	Sum of	% Contribution	
i urumeter	Effects	Squares		
Voltage Open	0.7	1.46	7.44	
Intensity of Pulse	-1.26	4.73	24.18	
Stabilizer A	0.064	0.012	0.064	
Stabilizer B	0.45	0.6	3.05	
Stabilizer E	0.88	2.34	11.97	
Voltage Gap	-0.18	0.1	0.51	
Wire Speed	-0.21	0.13	0.65	
Wire Tension	1.16	4.03	20.57	
Rotational Spindle	1 36	5 55	28.24	
Speed	1.50	5.55	20.34	
Feedrate	0.15	0.066	0.34	
Spindle Direction	0.43	0.57	2.9	

Table 4.5: Percentage contribution of S/N ratio for Ra



Figure 4.3: Summarization of hybrid micro WEDT operating conditions percentage contribution to the Ra by employing Taguchi Orthogonal Array  $L_{12}$ 

Parameter	Level 1	Level 2	Delta	Rank
Voltage Open	-15.03	-14.34	0.7	5
Intensity of Pulse	-14.06	-15.31	1.26	2
Stabilizer A	-14.72	-14.65	0.06	11
Stabilizer B	-14.91	-14.46	0.45	6
Stabilizer E	-15.13	-14.24	0.88	4
Voltage Gap	-14.59	-14.78	0.18	9
Wire Speed	-14.58	-14.79	0.21	8
Wire Tension	-15.26	-14.11	1.16	3
Rotational Spindle	-15 37	37 -14.01	1.36	1
Speed	10107		1.00	
Feedrate	-14.76	-14.61	0.15	10
Spindle Direction	-14.9	-14.47	0.43	7

Table 4.6: Response table for Signal to Noise Ratios

Smaller is better

For the purpose of obtaining the P-value, the stabilizer A as parameter is excluded to allow the analyzation by ANOVA in Minitab Software. Stabilizer A has been left out during ANOVA because the contribution of that factor is measly (Roy, 2001). According to (Roy, 2001), at least one of the less influences factor need to be excluded in order to performs the ANOVA for Taguchi OA. Table 4.7 shows the result for ANOVA to further analyse statistically the effects of operating conditions on Ra. ANOVA is used to identify the significance among the parameters on the Ra in statistical point of view. The ANOVA results indicate that the most significant factors according to the lowest P-value are rotational spindle speed, intensity of pulse, wire tension and stabilizer E. Other than that, voltage open has approached an acceptable significance level with P-value of 0.059. The other parameters possess none statistical effects on Ra with massive P-value is greater than 0.05.

Source	DF	Adj SS	Adj MS	<b>F-Value</b>	<b>P-Value</b>
Regression	10	19.5622	1.95622	156.86	0.062
Voltage Open	1	1.4555	1.45549	116.71	0.059
Intensity of Pulse	1	4.7323	4.73233	379.45	0.033
Stabilizer B	1	0.5967	0.59667	47.84	0.091
Stabilizer E	1	2.3429	2.34294	187.86	0.046
Voltage Gap	1	0.0999	0.09987	8.01	0.216
Wire Speed	1	0.1278	0.12783	10.25	0.193
Wire Tension	1	4.0266	4.02664	322.87	0.035
Rotational Spindle Speed	1	5.5469	5.54687	444.76	0.030
Table Feedrate	1	0.0664	0.06639	5.32	0.260
Spindle Direction	1	0.5672	0.56722	45.48	0.094
Error	1	0.0125	0.01247		
Total	11	19.5747			

Table 4.7: S/N ratio ANOVA for Ra

One of the objectives of employing Taguchi method is to recognize the effects of factors on declared performance measures. Among the factors studied, rotational spindle speed, pulse intensity and wire tension are dominating the Ra value as listed in Table 4.5 and Figure 4.3 by referred to percentage contribution with 20% and above to the surface roughness results. If compared with stabilizer E, it has only approximately 10% contribution to the surface although it has statistical significant by referred to the ANOVA. Figure 4.4 shows the main effects of the S/N ratio for each of the process parameters is that conducted by hybrid WEDT for turning micro-cylindrical parts. Taguchi employs signal-to-noise (S/N) ratio to maximize the robustness of the operating conditions. The loss function is able to be minimized by maximizing the value of the S/N ratio. The S/N ratio plots for these three factors have shown dramatic trend line by changing the level of the parameter. For pulse intensity, by increasing the parameter level 8 to 10 Notch, the Ra increases. The low Ra is able to be achieved at 8 Notch. This could be explained in terms of energy produced in the erosion process. By increasing the pulse intensity, it will lead to the increase of the energy which has generated large size of crater (Giridharan and Samuel, 2015).



Figure 4.4: Main effects plot for S/N ratios of Ra results

For rotational spindle speed and wire tension, the lowest Ra is generated by high parameter level. From the S/N ratio of rotational spindle speed plotted, it depicts the lowest Ra achieved by using 2400 rev/min. By increasing the spindle speed from 50 rev/min to 2400 rev/min, the Ra dramatically decreases. These results are consistent with data obtained by Mohammadi et al. (2008a); Haddad et al. (2010). The lowest surface roughness value is produced by increasing rotational spindle speed with constant feedrate table because of the synchronization between spindle speed and table feedrate in producing tight pitches on the machined that influenced low Ra value as found by Qu et al. (2002b).

Furthermore, from the S/N ratio of wire tension plotted, the graph indicates that the lowest Ra is obtained by using 14.8 Newton tension of electrode wire. This result corresponds with previous researches done since it seems that the higher tension of electrode wire leads to lesser deflection of the wire which then produces smoother surface roughness

(Shah et al. 2011). Additionally, the S/N ratio plot also shows the effects of voltage open on surface roughness. By increasing the voltage open from 6 to 8 Notch the Ra value drops. Contrary to expectations and previous studies, these voltage results do not find similar trends like pulse intensity. However, these results are in agreement with those obtained by Mohammadi et al. (2008b) which indicates that voltage does not has statistical significant effects on the Ra with P-value = 0.059 (Table 4.7).

According to Mitsubishi RA90 parameter library, stabilizer B is specified as the switch to obtain machining stability. This stabilizer B is related to the off time in pulse waveforms. The higher the value, the off time of machining process occurs highly frequent which also generates slower machining process. The Ra value decreases by increasing the level parameter from 6 to 12 Notch which means the number of sparks fall off. Among all the process parameters, only spindle direction is categorized as categorical factor. As shown in surface roughness S/N ratio plotted, the downward direction produces the lowest Ra value. Since this phenomenon has not been found elsewhere in the previous literatures, it is probably related to the arcing that occurs more frequently due to the spark gap that becomes smaller when the spindle is rotated in opposite to the electrode wire travelling (upward direction) which leads the machined surface to be deteriorated. The phenomenon of these results is further investigated in scientific perspective which will be covered in the next section. Apart from spindle direction, stabilizer E also has obvious result on the Ra value.

According to Mitsubishi RA90 parameter library, stabilizer E is also specified as the switch for controlling the machining stability. By setting the Notch value at high level, the machining process becomes slower but wire is difficult to break. This occurrence also will be covered in the next section for better understanding in terms of the waveforms. As indicated by Table 4.5, the less influenced parameters on the Ra in this study that possess less than 1% of contribution percentage are wire speed, voltage gap, table feedrate and

stabilizer A. The result of the S/N ratio plotted is useful to extract the comprehensive optimization in this study. The suggestion of each parameter level is considered to generate low Ra value as indicated by Table 4.6 and Figure 4.4 is used for further parameter optimization in next section which serves as fixed level on respective parameter.

# 4.3.3 Summary of Screening Analysis

The objective of this screening analysis is to obtain the parameter that is highly influenced to the surface roughness results for application of comprehensive parameter optimization by using RSM. Therefore, the outcome of this screening process should contribute to providing small number of the parameter for optimization by RSM. Apart from that, the range for each of the parameter is scaled down for obtaining best fits mathematical model. Meanwhile, the other parameters that are not selected remain fixed at the best level in order to produce low Ra value. Based on the results, the selected parameter to perform comprehensive parameter optimization by using RSM are intensity of pulse, voltage open, wire tension and rotational spindle speed as shown in Table 4. 8 and Table 4.9. The other parameters are fixed at best level for producing low Ra value that will be discussed in the next section. The scientific discussion for selected parameters also will be covered in the next session.

Parameter	Level 1	Level 2	Delta	Rank	Decision
Voltage Open	-15.03	-14.34	0.7	5	Selected
Intensity of Pulse	-14.06	-15.31	1.26	2	Selected
Stabilizer A	-14.72	-14.65	0.06	11	Fixed
Stabilizer B	-14.91	-14.46	0.45	6	Fixed
Stabilizer E	-15.13	-14.24	0.88	4	Fixed
Voltage Gap	-14.59	-14.78	0.18	9	Fixed
Wire Speed	-14.58	-14.79	0.21	8	Fixed
Wire Tension	-15.26	-14.11	1.16	3	Selected
Rotational Spindle	-15 37	-14 01	1.36	1	Selected
Speed	15.57	-14.01			Sciected
Feedrate	-14.76	-14.61	0.15	10	Fixed
Spindle Direction	-14.9	-14.47	0.43	7	Fixed

Table 4.8: Selection of the parameters for RSM based on rank

Table 4.9: Selected fixed and vary parameters with respective to best level and range for RSM

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Parameter		Level and Range			
Stabilizer A		Level 2- 3 Notch			
Stabilizer B		Level 1- 12 Notch			
Stabilizer E		Level 2- 5 Notch			
Voltage Gap	Fixed	Level 1- 40 volts			
Wire Speed	-4	Level 1- 10 Notch			
Table Feedrate		Level 2- 0.1 mm/min			
Spindle Direction	ΝΙΚΑΙ	Level 2- Downward			
Voltage Open		6 to 8 Notch			
Intensity of Pulse	Vom	8 to 10 Notch			
Rotational Spindle Speed	vary	400 to 2400 rev/min			
Wire Tension		12.2 to 14.8 Newton			

# 4.3.4 Scientific Finding

According to Table 4.8 and Table 4.9, only four parameters are being selected for the optimization which are intensity of pulse, voltage open, wire tension and rotational spindle speed. By comparing the voltage open and stabilizer E, the voltage open is selected for further optimization stage because stabilizer E possesses imprecise details of the waveforms.

The basic explanation about the waveforms of stabilizer E is referring to the Mitsubishi RA90 machine manual and is related to the hybrid micro WEDT fundamental waveforms. Apart from stabilizer E, spindle direction also still does not have specific scientific explanation regarding the influences of the direction of the spindle rotation on performance measures. Meanwhile by developing an appropriate understanding and solutions on spindle rotation direction, the accuracy of the result estimation is able to be enhanced.

## 4.3.4.1 Stabilizer E

According to Mitsubishi RA90 parameter library, stabilizer E is specified as the switch for controlling the machining stability. As the Notch value increases, the machining becomes slower but wire is difficult to break. By referring to the pulse waveforms that is provided by Mitsubishi RA90 as cover in Chapter 3, the stabilizer E is fundamentally denoted as short/arc circuit current controller. As previously mentioned and proved by results of S/N ratio and ANOVA, stabilizer E proves to have statistical significant effects on Ra value. Therefore, this phenomenon is related to the abnormality on WEDM process but it is normal in WEDT (Janardhan and Samuel, 2010; Rees, 2011).

In WEDT, the presence of the rotary axis mechanism in WEDM inadvertently changes the characteristic of the pulses. Figure 4.5 shows the waveforms comparison between WEDT and WEDM from this research study. Compared to the WEDM, the waveforms for WEDT contain lots of arc region which means the energy to produce the plasma is not sufficient.

According to Rees (2011), the rotating workpieces lead to increasing variation of the discharge gap channel. He found that the pulse on time for a rotating workpiece in  $\mu$ WEDM is higher compared to the motionless workpieces. Explanation for this phenomenon is that the stable discharge channels cannot be maintained over long pulse on time when the

discharge channel is interrupted by a rotating workpiece. Therefore, inadequate discharge energy is produced which differs to the static workpieces whenever the discharge energy remains unchanged. Another studies by Janardhan and Samuel (2010), there are more formation of arcs and arc region occur compared to WEDM due to reduction of spark gap during erosion process. During the discharged, the material is removed from rotating workpieces and at the same time the wire is fed forward.

It might be concluded that, by interference of rotating workpieces during machining by WEDM, the arcing occurs more frequently. The advantage of Mitsubishi RA90 WEDM machine is that it is capable to control the short/arc current during machining. However, without the proper setup of pulse waveforms acquire system in order to collect the information of the pulse for stabilizer E during machining, the stabilizer E is excluded in this present study.

The stabilizer E is replaced with voltage open because it possesses a clear tendency to has statistical significance on Ra with P-value 0.059 associated with lots of the research works in EDM field that include voltage open as the process parameter since the current and voltage are keys to create the plasma channel.



Figure 4.5: Comparison of pulse trains a) WEDM and b) Hybrid Micro WEDT

# 4.3.4.2 Spindle Direction

There are two preliminary assumptions in explaining the rough surface roughness for upward spindle direction condition as indicated from the Taguchi screening results. First, by applying upward direction of spindle rotations, lots of arcing sparks presume to be occurred because insufficient energy generated by arc pulses itself leads to deteriorating the surface roughness. Another assumption is, the result of the rough surface roughness is presumed to be initiated by the fragments that re-solidify on part machined surface.

The fundamental of WEDT is that when the discharge arises, the material is removed from the rotating workpiece simultaneously and the electrode wire is fed forward which leads the un-machined portion of the workpiece to face the wire then spark gap manages to reduce.

This occurrence increases the formation of arcs and arc regions WEDT (Janardhan and Samuel, 2010). When the spindle direction moves in the opposite to the electrode wire travelling (upward direction), the gap between the workpiece and electrode wire is reduced. Therefore, the number of arc pulses and number of arc regions increase on that occasion, thus deteriorating the machined parts surface finish.

Other than that, in upward spindle direction, the flushing of the fragments is certainly less effective because the electrode wire traveling push the fragments to the exit of wire direction (downward). At the same time, the rotating spindle forces the fragments to the direction of the wire entry (upward), thus the fragments that should be flushed away by kinetic energy of centrifugal force is slowing down until it remains and solidifies again to the machined surface. This circumstance is illustrated in Figure 4.6 and Figure 4.7 for better understanding of the phenomenon.



Figure 4.6: Movement of fragments while encountering dissimilar force direction for upward spindle direction



Figure 4.7: Movement of fragments while encountering similar force direction for downward spindle direction

Under this inadequate flushing effect, the conducting particles grow to such a concentration that links between the electrode that promises short circuits and arcs pulses mechanism rather than normal sparks (Kumar and Choudhury, 2007). The surface roughness also has been damaged by the adherence of re-solidified eroded particles that are capable to form recast layer (Qu et al. 2002b; Kumar et al. 2016; Kumar and Choudhury, 2007).

Therefore, the series of the preliminary experiment is being conducted for obtaining and explaining the influences of spindle direction (upward and downward) on surface roughness related to the fragments that re-solidify to the machined surface. The experiment only considered the spindle direction as input factor and other parameters are kept constant. Spindle direction has upward and downward direction. Figure 4.8 shows the fragments removal progression by ultrasonic vibration at 27 kHz of frequency by ultrasonic bath cleaner immersed by cleaning type ethanol. The comparison is made between the different spindle direction effects on the progression of the fragments removed by ultrasonic cleaner in order to prove the re-solidified fragments of the machined surface.

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Figure 4.8: The progression of the fragments removal by ultrasonic

The high spindle speed for upward direction convincingly would produce lots of fragments that previously unable to be flushed during machining compared to the downward direction of spindle rotation. When it is cleaned by ultrasonic bath, the progression of fragments removed is clearly detached from the machined surface as indicated by Figure 4.8. For upward direction result, it clearly shows the quantity fragments removed is high per unit time before it remains steady around 280 minutes. Compared to the downward direction, less of the fragments is removed and it remains steady at faster rate around 250 minutes.

This figure (Figure 4.8) explains the large amount of re-solidified fragments at upward direction than downward direction. The steady states of the figures probably indicate the actual mass of the Ti6Al4V specimen. Hence, it could conceivably be hypothesised that the upward direction of the rotating spindle is incapable to flush away the fragments, and consequently the fragments remains and re-solidifies as forced by unequal vector and magnitudes between rotating workpiece and electrode wire travelling. The concentration of fragments may result in bridging both of the electrodes in machining gap, inadvertently expels the arc and short pulses.

# 4.4 Parameter Optimisation by Employing Face-centred Central Composite Design (FCCD)

#### 4.4.1 Assessing Process Parameters by using Statistical Analysis

The statistical combination of variables which is being used for optimization is referred to the design scheme based on Table 3.13 in section 3.5.1. The experimental trials are conducted focusing on the surface roughness as response and the results shown in

Table 4.10, the Ra value varies between 4.277  $\mu$ m to 4.672  $\mu$ m from all the experiments. It can be observed that the combination of low intensity of pulse (8 Notch) and voltage (6 Notch) between high wire tension (14.8 N) and spindle speed (2400 rev/min) produces the lowest Ra as much as 4.277  $\mu$ m. Meanwhile, the combination of high intensity of pulse (10 Notch) and voltage (8 Notch) with low wire tension (12.2 N) and spindle speed (400 rev/min) produces the highest Ra as much as 4.672  $\mu$ m.

	AsTransita			<b>D:Rotational</b>	
Experimen	t A:Intensity	<b>B:Voltage</b>	<b>C:Wire Tension</b>	Spindle	Ra
Number	of Pulse			Speed	
	(Notch)	(Notch)	(Newton)	(rev/min)	(µm)
1	8	6	12.2	400	4.473
2	10	6	12.2	400	4.531
3	8	6	14.8	400	4.420
4	10	6	14.8	400	4.571
5	8	6	12.2	2400	4.395
6	10	6	12.2	2400	4.415
7	8	6	14.8	2400	4.277
8	10	6	14.8	2400	4.380
9	8	8	12.2	400	4.634
10	10	8	12.2	400	4.672
11	8	8	14.8	400	4.561
12	10	8	14.8	400	4.607
13	8	8	12.2	2400	4.508
14	10	> 8	12.2	2400	4.560
15	8	8	14.8	2400	4.387
16	10	8	14.8	2400	4.493
17	SAIN 9	7	13.5	1400	4.453
18	9	7	13.5	1400	4.473
19	لىسا ملاك	1, 9-2	13.5	1400	4.469
20	9	7	13.5	1400	4.462
21	INIVER9SITI	ТЕКЛІКА	L MA13.5YSIA	ME 1400	4.435
22	9	7	13.5	1400	4.451
23	8	7	13.5	1400	4.417
24	10	7	13.5	1400	4.504
25	9	7	12.2	1400	4.481
26	9	7	14.8	1400	4.368
27	9	7	13.5	400	4.509
28	9	7	13.5	2400	4.404
29	9	6	13.5	1400	4.452
30	9	8	13.5	1400	4.585

 Table 4.10: Surface roughness result

Furthermore, in developing the adequate polynomial equation for the Ra as responses, three different tests are performed which are sequential model sum of square, lack of fit test and model summary statistics presented in Table 4.11, Table 4.12 and Table 4.13

respectively. The results indicate that quadratic model with two-factor interaction is suggested with very low probability (P-value) of 0.0003 and the F-value of 10.719 is large enough to validate a very high degree of appropriateness of the model and also directs that the treatment combinations are highly significant (Khuri and Cornell, 1987). The Model F-value of 10.719 implies that the model is significant and there is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. The model summary statistics (Table 4.13) suggests quadratic model focuses on the summarization for model by maximizing the adjusted coefficient of determination (R<sup>2</sup>) and the predicted R<sup>2</sup>. However, both of this value ae able to be maximized by excluding the terms that are not significance or less influenced from contributing to the model.

Table 4.14 and Table 4.15 show the ANOVA by employing the reduced quadratic model and found to be the most suitable model with adjusted R<sup>2</sup> and predicted R<sup>2</sup> as much as 0.957 and 0.916 respectively. The predicted R<sup>2</sup> of 0.916 is in reasonable agreement with the adjusted R<sup>2</sup> of 0.957. This specifies that the model obtained will be able to give a good estimation of the response of the system in the experimental range studied. In addition, the adequate precision is also found to be 37.87. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is considered to be desirable.

Other than that, the ANOVA also signifies that the model possesses the P-value less than 0.05 which means the polynomial equation that is generated is able to represent the actual experimental condition between process parameters and the Ra. This is further proved from the lack of fit test which indicates that the reduced quadratic model has insignificant P-values. The "Lack of Fit F-value" of 1.93 implies the lack of fit is not significant relative to the pure error. There is a 24.14% chance that a "Lack of Fit F- value" this large could occur due to noise. Therefore, the model can be used to navigate the design space. The following quadratic surface model has been accordingly chosen as the final model: Ra = 4.623524 - 0.116865\*Intensity of Pulse - 0.740501\*Voltage + 0.407668\*Wire Tension + 0.000060\*Rotational Spindle Speed + 0.011378\*Intensity of Pulse\*Wire Tension - 0.007660\*Voltage\*Wire Tension - 0.000009\*Wire Tension\*Rotational Spindle Speed + 0.064613\*Voltage\*Voltage - 0.017389\*Wire Tension\*Wire Tension

Sequential Model Sum of Squares [Type I]										
	Sum of Mean F P-value									
Source	Squares	df	Square	Value	Prob > F					
Mean vs Total	601.62826	1	601.62826							
Linear vs Mean	0.18566	4	0.04642	38.294	< 0.0001					
2FI vs Linear	0.00790	6	0.00132	1.118	0.3890					
Quadratic vs 2FI	0.01659	4	0.00415	10.719	0.0003	Suggested				
Cubic vs Quadratic	0.00466	8	0.00058	3.580	0.0550	Aliased				
Residual	0.00114	7	0.00016							
Total	601.84422	30	20.06147	5						
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Table 4.11: Sequential model sum of squares analysis for surface roughness model

Table 4.12: Lack of fit test for surface roughness model

	and the second second	The second se	100	100		and the second se
Source	Sum of		Mean	F	P-value	
Source	Squares	df	Square	Value	Prob > F	KA
Linear	0.02936	20	0.001468	7.787	0.0158	
2FI	0.02145	14	0.001532	8.129	0.0151	
Quadratic	0.00486	10	0.000486	2.579	0.1537	Suggested
Cubic	0.00020	2	0.000099	0.524	0.6214	Aliased
Pure Error	0.00094	5	0.000189			

Table 4.13: Model summary statistics for surface roughness model

Source	Std Dev	P Squared	Adjusted	Predicted	DDESS	
	Stu. Dev.	R-Squared	<b>R-Squared</b>	<b>R-Squared</b>	I KLSS	
Linear	0.0348	0.8597	0.8372	0.7925	0.0448	
2FI	0.0343	0.8963	0.8417	0.6856	0.0679	
Quadratic	0.0197	0.9731	0.9480	0.8341	0.0358	Suggested
Cubic	0.0128	0.9947	0.9781	0.7721	0.0492	Aliased

Courses	Sum of	46	Mean	F	P-value	
Source	Squares	ai	Square	Value	Prob > F	
Model	0.2096	9	0.0233	72.80	< 0.0001	significant
A-Intensity of Pulse	0.0243	1	0.0243	75.96	< 0.0001	
B-Voltage	0.0662	1	0.0662	207.11	< 0.0001	
C-Wire Tension	0.0204	1	0.0204	63.92	< 0.0001	
D-Rotational Spindle Speed	0.0747	1	0.0747	233.44	< 0.0001	
AC	0.0035	1	0.0035	10.94	0.0035	
BC	0.0016	1	0.0016	4.96	0.0376	
CD	0.0023	1	0.0023	7.15	0.0146	
B <sup>2</sup>	0.0144	1	0.0144	44.96	< 0.0001	
C <sup>2</sup>	0.0030	1	0.0030	9.30	0.0063	
Residual	0.0064	20	0.0003			
Lack of Fit	0.0055	15	0.0004	1.93	0.2414	not significant
Pure Error	0.0009	5	0.0002			
Cor Total	0.2160	29				

Table 4.14: ANOVA for response of surface roughness

Table 4.15: R-squared analysis for response surface quadratic model of surface roughness

Ste	Std. Dev.	0.018	R-Squared	0.970	اونيا
	Mean	4.478	Adj R-Squared	0.957	
UNIV	C.V. %	0.399	Pred R-Squared	0.916	AKA
	PRESS	0.018	Adeq Precision	37.870	

As an additional step to determine the adequacy of the final model, a quick and effective tool for diagnosing residuals is by using the normal plot of residuals as shown in Figure 4.9. The plot indicates that there is no indication of non-normality, or possible outliers. It clearly shows a normal distribution of errors which implies the regression model is adequate where residuals obey a normal distribution in a scatterplot linear line. Other than that, Figure 4.10 shows parity charts for the prediction against actual values for arithmetic average surface roughness. The colour scale on the parity charts gives an indication of low and high values with blue being low and red being high.



Figure 4.9: Model validation plot for Normal % probability of internally studentized residuals



Figure 4.10: Model validation plot for relationship between the observed and the predicted

# 4.4.2 Comparative and Determination of Significant Terms on Surface Roughness

The comparative among the parameters is illustrated by perturbation plot (Figure 4.11) to deliver comprehensive summary. Additionally, referring to the ANOVA results (Table 4.14), the statistical significant terms on Ra are A, B, C, D, AC, BC, CD, B<sup>2</sup>, C<sup>2</sup> where the confident level is less than 0.05. Based on these results, there are two-interactions among the terms namely AC, BC and CD are further discussed in this section.



Figure 4.11: Perturbation plot for surface roughness performance

As shown in Figure 4.11, the perturbation plot shows the comparative effects of significant factors on the Ra. By default, Design-Expert software sets the reference point at the midpoint (coded value 0) of all factors. Steep slope or curvature represents that the response is sensitive to that factors. Otherwise, no flat line for specifying the response is

insensitive to the change in that particular factor. The perturbation plot could also be used to find those factors that most affect the response. A steep slope for rotational spindle speed (D) is highly sensitive followed by voltage (B), intensity of pulse (A) and wire tension (C). In addition, the trends for A and B have similar figuration. By increasing the respective parameter value, the Ra value increases. Other than that, the trends for C and D also have similar figuration. By increasing the respective parameter value, the Ra value increases. Other than that, the trends for C and D also have similar figuration. By increasing the respective parameter value, the Ra reduces. It can be concluded that the effects of intensity of pulse (A) and voltage (B) are directly proportional on Ra which differs for wire tension (C) and rotational spindle speed (D) as they are inversely proportional to Ra. Ra has statistical significance effects and decreases with the decrease of A and B from 10 to 8 Notch, 8 to 6 Notch and increases the rotational spindle speed from 400 to 2400 rev/min and wire tension from 12.2 to 14.8 N. According to literatures, these results are in accord with recent studies indicating that intensity of pulse, voltage, wire tension and rotational spindle speed play a part in surface finish as well as possess significant terms in statistical perspective.

Intensity of pulse and voltage are known as the primary electrical parameter in producing the plasma channel either in EDM, WEDM or WEDT (Kojima et al. 2008). These factors normally influence the size of crater produced by erosion process of plasma implosion. Therefore, these parameters indirectly affect the surface roughness because the arithmetic average surface roughness depends on the size of spark crater. It has conclusively been shown that the plasma channel is created by ionization of discharge energy. The energy used for the material removal is only contributed by the voltage and pulse intensity during erosion process as stated by Yeo et al. (2007). The higher voltage is related to larger discharge energy, thereby producing higher plasma temperature that causes violent sparks and resulting in a deeper erosion crater on the surface and more material is removed (Nagahanumaiah et al. 2009). Admittedly, in this present study, voltage and intensity of pulse are being dominated and statistical significance factors contribute to the Ra value.

From the perspective of electrode wire tension, it seems that the higher wire tension applied during machining is able to minimize the deflection of the wire and subsequently generates the smoother surface. The even pitches or formation of the macro-ridges during machining remains in steady state due to the restrained flexibility of the tensed wire. However, the even pitches or formation of the macro-ridges that attempts retained is certainly interrupted if the low tension of the electrode wire is selected. There are similarities between the characteristics expressed by wire tension on surface roughness in this study and those described by Ekici et al. (2015); Ikram et al. (2013); Pramanik (2015); Shah et al. (2011); Mohammadi et al. (2010). The researchers solidly conclude that by increasing the wire tension, the excellent surface roughness finish can be obtained. Figure 4.12 explains the example of the workpieces surface that machined by hybrid micro WEDT which contain with obvious occurrence of macro-ridges.



Figure 4.12: The occurrence of macro-ridges in hybrid micro WEDT workpiece machined surface

In terms of rotational spindle speed, the finding is consistent with findings of past studies by Mohammadi et al. (2008a); Giridharan and Samuel (2015); Haddad et al. (2010). The surface finish improves by increasing rotational spindle speed and by keeping constant of the feedrate table. Among the plausible explanations for these findings are categorized to two types of phenomena. First, is the synchronization between spindle speed and table feedrate in producing pitches/macro-ridges on the machined surface that affects the surface roughness. Theoretically, the tight pitches produce low Ra value as found by Qu et al. (2002b). The synchronization of high rotational spindle speed with slow table feedrate will produce smoother surface. However, in electrical discharges sparking phenomenon, Qu et al. (2002b) pointed that the experimental values of Ra are much higher than the theoretical ALAYS/A Ra to the additional craters on the EDM surface. Second phenomenon is related to pulse characteristics. The most striking scientific explanation is stated by Janardhan and Samuel (2010), when high rotational spindle speed is applied, the circumferential length of the material crossing the spark region per unit time increases that leads to energy reduction and inadvertently producing low value of surface roughness on machined surface.

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Figure 4.13: Response surface showing the interactive effect of intensity of pulse and wire tension on surface roughness at rotational spindle speed = 1400 rev/min and voltage = 7 Notch

Figure 4.13, illustrates the estimated response surface roughness in function of the factors of intensity of pulse and wire tension (AC). The low value of Ra is produced by reducing the intensity of pulse (A) and the use of high value wire tension (C). It is clearly seen in Figure 4.13, intensity of pulse (A) has increased trend line at high and low value of parameter and wire tension has initially decreased trend line only at low value of pulse intensity but not at high value, the surface roughness has slightly increased and suddenly dropped by varying the wire tension levels of parameter when the high level of pulse intensity is used. However, at lower wire tension (12.2 N), the slope is less steep for intensity of pulse than at high wire tension. Although, at high intensity of pulse, the wire tension slope is less steep than at low value of intensity of pulse. High Ra is produced at low wire tension

(12.2 N) and at high level of intensity of pulse (10 Notch). Based on ANOVA, the intensity of pulse is the dominating factor compared to wire tension.

Undoubtedly, the interaction between intensity of pulse and wire tension has triggered the surface roughness value as earliest reported by Song et al. (2013). Song et al. (2013) discovered that the usage of the strip electrode as replacement on electrode wire in WEDT is able to produce nearly equal surface roughness value with varying intensity of pulse. However, by using wire as electrode, the surface roughness becomes deteriorated by increasing intensity of pulse. These phenomena explain that by increasing the intensity of pulse, the sparks continue to occur in the extreme modal positions of the wire which leads to high vibration of wire that destructs the machined surface. It is interesting to note that this circumstances has clearly been depicted on machined surface which is the occurrence of cusps (Song et al. 2013) also known with the name macro-ridges (Qu et al. 2002b). During sparks erosion, the discharge reaction force becomes the dominating cause on wire deformation as stated by Zhang et al. (2014). The wire vibration turns out to be more serious as wire tension decreases at high intensity of pulse. This circumstances reflects the findings of Maher et al. (2015) that mentioned the lowest value of intensity of pulse and the highest value of wire tension are the best choice to attain a low surface roughness value, which is in good agreement with the results of the present study.



Figure 4.14: Response surface showing the interactive effect of wire tension and voltage on surface roughness at rotational spindle speed = 1400 rev/min and intensity of pulse = 9 Notch

Figure 4.14, illustrates the estimated response surface roughness in function of the factors of wire tension and voltage (BC). The low value of Ra is produced at low tension of wire (C) and by reducing the value of voltage (B). The high value of Ra is clearly produced at high voltage and low tension of wire. As shown in Figure 4.14, voltage greatly indicates influences on surface roughness compared to wire tension at low and high of the wire tension. Compared to the interaction between wire tension (C) and intensity of pulse (A) as previously discussed, the influence of wire tension has relatively flat line on voltage in between low and high value tension of wire.

It is interesting to note that this phenomenon clearly depicts the fundamental of EDM principles. During erosion process, as soon as the breakdown occurs, the voltage falls and a current rises abruptly. At this stage, the current is permitted since the dielectric has been

ionized and a plasma channel has been created between the electrodes. In this state, the discharge current is then maintained to ensure the continuous bombardment of ions and electrons on both of the electrodes. It is apparent from this phenomenon describing the interaction between wire tension and intensity of pulse. The discharge current is remained constant to assure the sparks continuous bombard to the workpieces leads to wire terribly deflects conform destruction of the machined surface. However, voltage plays less role in this state. Voltage only serves amount of pulses through the small gap in giving rise to electrical breakdown (Giridharan and Samuel 2015) as well as contributing to the creation of discharged energy during pulse on time (Yeo et al. 2007). According to the Figure 4.14, the maximum surface roughness predicted by response surface in this experiment clearly interacted between low wire tension (12.2 N) and high voltage (8 Notch). The higher the voltage relates to the larger the discharged energy, in that way producing higher plasma temperature that causes violent sparks and results in a deeper erosion crater on the surface and more material is removed (Nagahanumaiah et al. 2009).

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Figure 4.15: Response surface showing the interactive effect of rotational spindle speed and wire tension on surface roughness at intensity of pulse = 9 Notch and voltage = 7 Notch

Figure 4.15, illustrates the estimated response surface roughness in function of the factors of wire tension and rotational spindle speed (CD). The low value of the Ra is produced at high rotational spindle speed (D) and wire tension (C).

As shown in Figure 4.15, rotational spindle speed has decreased trend line at high and low value of parameter and wire tension has initially decreased trend line only at high speed of spindle but when applying low of the spindle speed, the surface roughness has slightly increased and then marginally fell by varying the wire tension levels from low to high tension of wire. Other than that, rotational spindle speed has high influence on Ra compared to wire tension as indicated by the steeper respective slope. Furthermore, at lower rotational spindle speed (400 rev/min), the wire tension slope is less steep than at high rotational spindle speed (2400 rev/min). Meanwhile, the rotational spindle speed slope is less steep at low wire tension (12.2 N) than at high tension of wire (14.8 N).

The poor surface roughness is produced by the interaction between the low rotational spindle speed (400 rev/min) and low tension of wire (12.2 N). In this circumstance, the pitches/ridges certainly formed by 400 rev/min of spindle speed are theoretically six times more coarser than 2400 rev/min which then accompanied by presence of the electrode wire deflection due to low tension of electrode wire that promises rough surface roughness. In contrast, fine surface finish is produced with arrangement of high rotational spindle speed with large tension of electrode wire in capability to reduce the wire flexibility during bombardment of ions and electrons in the erosion process.

As previously discussed, by applying high speed spindle rotation, tight pitches/ridges are produced that leads to smooth surface roughness. However, if that steady state during erosion process is interrupted by high amplitude of wire deflection (low wire tension), the uneven pitches/macro-ridges will occur. The irregular pitches/macro-ridges lead to rough surface finish. It can be noticed from the surface topography result that will be covered in next section that the surface finish becomes more serious as wire tension decreases. This interaction result also can be inferred that a fine surface roughness can be achieved by using a stable and high wire tension as agreed by Liao and Yu (2004).

# 4.4.3 Model Validation

The accuracy of the developed response surface model is validated by confirmatory experiment through the residual error between prediction and experiment. The accuracy between the prediction and experimentation is done by assessing the amount of the relative error by using the equation below;

$$Relative \ Error \ (\%) = \left| \frac{(Predicted \ Value - Actual \ Value \ )}{Predicted \ Value} \right| \times 100$$

To evaluate the suggested mathematical model that produced by the experimental works, a series of the ten parameter sets were performs which are selected based on the new combinations of non-generated by FCCD design scheme are shown in Table 4.16. The new combinations that proposed in this section is not similar with the FCCD design scheme that is suggested by Design Expert software as indicated in

Table 4.10 to challenge mathematical model to work well on various of parameter levels. The relative error falls within the 90% prediction interval and the residual errors range from 0.241% to 4.499% which are in absolute value that are less than 10%. This indicates that the model is accurate enough to predict the Ra within 90% of confidence interval and the residual errors relative to predicted values are less than 10%. Figure 4.16 shows the comparison between the predicted and experimentation Ra result for confirmatory experiment.

	A:	D.	C. Wing	D:	Ra			
Experiment Number	Intensity of Pulse	B: Voltage	C: Wire Tension	Spindle Speed	Experiment	Prediction	Error	
	(Notch)	(Notch)	(Newton)	(rev/min)	(μr	n)	(%)	
1	8	7	13.5	400	4.368	4.485	2.603	
2	9	7	12.2	400	4.312	4.514	4.471	
3	9	8	13.5	400	4.658	4.647	0.241	
4	10	7	13.5	400	4.571	4.558	0.280	
5	9	6	13.5	400	4.703	4.525	3.776	
6	8	7	12.2	1400	4.522	4.439	1.826	
7	9	7	13.5	1400	4.342	4.457	2.582	
8	10	8	13.5	1400	4.826	4.619	4.288	
9	8	7	14.8	1400	4.543	4.342	4.415	
10	9	7	14.8	2400	4.521	4.318	4.499	

Table 4.16: Result for confirmation experiments for estimated responses



Figure 4.16: Comparison of predicted to the actual validation for surface roughness (Ra)

# 4.4.4 Parameter Optimization

The ideal technique for selecting the optimum operating process parameters is by referring to desirability approach. Desirability value is in the range of 0 to 1 and if the desirability value equals to zero, it means the predicted value is undesirable and if the value equals to one, the desirability is idle. Higher desirability score of the resulting response reflects the better optimization in goal of minimizing the Ra value by hybrid WEDT in machining micro-cylindrical components (Tiwary et al. 2015). Figure 4.17 shows the example of the desirability approach in inserting the level and the range of each parameters by Design-Expert. The report begins with a summary of optimization specifications. Then, the Design-Expert software lists the solutions in order of desirability value.

Constraints							
		Lower	Upper	Lower	Upper		
Name	Goal	Limit	Limit	Weight	Weight	Importance	
Intensity of Pulse	is target = 8.00	8	10	1	1	3	
Voltage	is target = 7.00	6	8	1	1	3	
Wire Tension	is equal to 14.80	12.2	14.8	1	1	3	
Rotational Spindle Spee	ed is target = 2390.00	400	2400	1	1	3	
Ra	minimize	4.27667	4.672	1	1	3	
Solutions							
Numbe	er Intensity of Pulse	Voltage W	ire TensiorRe	otational S <sub>I</sub>	Ra	Desirability	
	1 <u>8.00</u>	7.00	14.80	2390.00	4.26684	<u>1.000</u>	Selected
	2 8.01	7.00	14.80	2389.99	4.26756	0.998	
	3 8.00	7.01	14.80	2390.00	4.26721	0.998	
	4 8.00	6.98	14.80	2390.00	4.26572	0.994	
	5 8.00	7.00	14.80	2310.19	4.27293	0.990	
	6 8.09	7.00	14.80	2389.99	4.2713	0.989	

Figure 4.17: Numerical optimization report on solutions by Design-Expert software

Since some of the process parameters are unable to be set within the range, the criteria of the parameters value are rounded and fixed at the specific value for obtaining lowest Ra value. The parameters are consisted of intensity of pulse, voltage and wire tension. Only rotational spindle speed can be adjusted within the range. However, the increment for spindle speed is as much as 10 rpm per adjusted. Therefore, the goal of the criteria is selected according to the parameters range ability. Table 4.17 shows the result of suggested and rounded value by desirability approach. At the end of the result, the optimum process parameter suggested is intensity of pulse as much as to be 8 Notch, wire tension of 14.8 Newton, voltage of 7 Notch and rotational spindle speed is as much as 2390 rev/min. Details of the approach of optimization for suit the Mitsubishi RA90 have been attached in Appendix E. The prediction of Ra value is as much as 4.26684 µm. If compared with the suggestion by Design-Expert software, the early Ra value is as much as 4.26763 µm, then after being adjusted because the machine is incapable to claim the exact suggested value for operation, the Ra is reduced to 4.26684 µm.

The confirmatory experiment is also being carried out and it has been found that the values of response parameters obtained through experimental work (Figure 4.18) are close with the predicted values as much as 4.0143 µm with error deviated 5.9% (Table 4.18). Figure 4.19 shows the perturbation plot for suggested optimum process parameter in this experimental work. As shown in ramp desirability graph (Figure 4.20), the suggested optimum surface roughness is generated below the lowest value that has been achieved in this experimental work with high value of desirability.

Stop	Parameter Suggested		Rounded	Ra (µm)		
Step	and Unit	Value	Value	Previous	After	
First Step	Intensity of Pulse (Notch)	8.14	8	4.26763	4.26804	
Second Step	Wire Tension (Newton)	14.7	14.8	4.26804	4.25749	
Third Step	Voltage (Notch)	6.51	7	4.25749	4.26697	
Fourth Step	Rotational Spindle Speed (rev/min)	EK2388.29L N	IAL23905IA	4.26697	4.26684	

Table 4.17: The approach of optimization to suit the Mitsubishi RA90 machine capability

Table 4.18: Optimal combination of input factors for single response optimization

	A٠			D:		Ra	
Optimization	Intensity	B: Voltage	C: Wire	Rotational Spindle	Fyn	Predict	Frror
Goal	of Pulse	voltage	Tension	Speed Exp.		Tredict.	LIIUI
	Notch	Notch	Newton	rev/min	μ	m	(%)
Minimizing							
the surface	8	7	14.8	2390	4.0143	4.2668	5.919
roughness							



Figure 4.18: Optimal surface roughness plot generated by Alicona software Infinite Focus



Figure 4.19: Perturbation plot of optimization for surface roughness at intensity of pulse = 8 Notch, voltage = 7 Notch, wire tension = 14.80 Newton and rotational spindle speed = 2390 rev/min with prediction result arithmetic average surface roughness =  $4.26684 \ \mu m$ 



Figure 4.20: Ramps report on numerical optimization for optimum surface roughness by Design-Expert software

# 4.4.5 Surface Topography of Hybrid Micro WEDT Surface

According to the previous section results, there are statistical significance results between tension of wire to pulse intensity, voltage and rotational spindle speed when they interact with each other. SEM and IFM are being used to examine the surface conditions of hybrid micro WEDT Ti6Al4V. The machined surface is examined on lateral surface of cylindrical parts.

# 4.4.5.1 Interaction between Intensity of Pulse and Wire Tension

Knowingly, the hybrid micro WEDT machined surface has the occurrence of macroridges but the results vary on the machining conditions either generated smooth or coarse roughness. As results of varying the pulse intensity interact to the tension of wire, the comparison is being made between the specimens experiment number 2 and 3. The micrograph result shows the specimen 2 (Figure 4.21) (high pulse intensity with low wire tension) generates unpleasant quality of texture compared to experiment number 3 (Figure 4.22) (low pulse intensity with high wire tension). When high intensity of pulse is applied in condition of low wire tension during sparks erosion by hybrid micro WEDT, the sparks repeatedly continue to occur in the extreme modal positions of the wire leads to wire vibrating, subsequently destructing the machined surface. It can be seen that the macro-ridges in specimen 2 possess uneven structure that is overly significant compared to specimen 3 which possesses medium smooth texture.



Figure 4.21: a) IFM micrograph b) SEM micrograph of hybrid micro WEDT machined surface (under Ra: 4.531: pulse intensity=10, voltage=6, wire tension=12.2, rotational spindle speed=400) experiment number 2



Figure 4.22: a) IFM micrograph b) SEM micrograph of hybrid micro WEDT machined surface (under Ra: 4.420: pulse intensity=8, voltage=6, wire tension=14.8, rotational spindle speed=400) experiment number 3

# 4.4.5.2 Interaction between Voltage and Wire Tension

The micrograph of the specimen number 9 (Figure 4.23) and 3 (Figure 4.24) are examined and compared. The bumpy rough surface roughness in specimen 9 has been revealed and compared to much smoother and better surface roughness in specimen 3. During spark erosion at high voltage interaction either in high or low wire tension leads to destroying the even surface texture by violent sparks produced by large discharged energy during pulse on time. The nature of voltage brings the potential difference of electric that is amplified together with electric current to the creation of discharged energy. The huge discharged energy will form strong sparks penetrating to the machined surface and subsequently erodes deeper crater.



Figure 4.23: a) IFM micrograph b) SEM micrograph of hybrid micro WEDT machined surface (under Ra: 4.634: pulse intensity=8, voltage=8, wire tension=12.2, rotational spindle speed=400) experiment number 9



Figure 4.24: a) IFM micrograph b) SEM micrograph of hybrid micro WEDT machined surface (under Ra: 4.420: pulse intensity=8, voltage=6, wire tension=14.8, rotational spindle speed=400) experiment number 3

# 4.4.5.3 Interaction between Rotational Spindle Speed and Wire Tension

Figure 4.25 and Figure 4.26 show the micrograph of the interaction between rotational spindle speeds to wire tension. Formation of pitches/ridges marks can clearly be seen when 400 rev/min (specimen number 10) is used compared to 2400 rev/min (specimen number 16), formation of pitches/ridges at 2400 rev/min in constricted manner. When low

tension of wire is applied to uneven formation of pitches/ridges, the coarser pitches/ridges are exacerbated by the deflection and vibration of the electrode wire that is struck by ions and electron. By chance, the high tension of wire regulates the machined surface from destructing the fine surface finish that is formed by high speed rotational spindle by keeping the electrode wire from vibrating and deflecting.



Figure 4.25: a) IFM micrograph b) SEM micrograph of hybrid micro WEDT machined surface (under Ra: 4,672: pulse intensity=10, voltage=8, wire tension=12.2, rotational spindle speed=400) experiment number 10



Figure 4.26: a) IFM micrograph b) SEM micrograph of hybrid micro WEDT machined surface (under Ra: 4.493: pulse intensity=10, voltage=8, wire tension=14.8, rotational spindle speed=2400) experiment number 16

#### 4.5 Summary

This chapter overall explains the results for achieving all the research objective to attain the optimized parameter for machining micro-cylindrical components by hybrid micro WEDT. The rotary axis mechanism that works well with WEDM machine has been successfully developed and performed the straight turning with maximum achievable diameter followed by contouring turning. The parameter optimization consideration on Ra begins with two stage screening. First, the suitable combination parameter and its range is properly selected. The incorrect combination among parameters and their range will result to the occurrence of wire breakage or insufficient electric sparks to erode. Then, the selection of appropriate parameters and range of further screening by Taguchi orthogonal array L<sub>12</sub> has been done. From the 11 process parameters that consist of electrical, non-electrical and rotary axis mechanism characteristics, only four that have been selected to perform optimization by RSM which are intensity of pulse, voltage open, wire tension and rotational spindle speed. The other parameters are fixed at best level to produce low Ra value which is identified by Alicona Infinite Focus microscope (IFM). The optimal Ra that is produced by experiment through desirability approach is as much as 4.0143 µm with relative error as much as 5.9% compared to the prediction. The machined parts surface is being deteriorated accordingly to the violent energy density generated by high pulse intensity and voltage, low wire tension and spindle speed.

#### **CHAPTER 5**

#### CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusion

The principal conclusion that has been revealed throughout this study is that the Ti6Al4V of micro-cylindrical components is fabricated by integrating a rotary axis mechanism on conventional WEDM machine known as hybrid micro WEDT. The process parameter for hybrid micro WEDT in fabricating this type of component is optimized for generating the lowest surface roughness value by predetermined goal and constraint which is straight turning operation with single pass cutting approach. The following conclusions are based on the analysis throughout the research. They provide general insight that reflects the objective of the research.

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# i. To develop and evaluate the rotary axis mechanism that can be incorporated with the WEDM machine for micro-cylindrical components fabrication

A rotary axis mechanism has been successfully developed and evaluated that suits for micro-cylindrical components fabrication by WEDM machine. The proper selection of the design and solution for rotary axis mechanism is according to the consideration among all the literatures survey. The commercialized parts and sub-parts are preferred to ease replaced for tear and wear parts. The resistance to corrosion of part materials is selected since hybrid micro WEDT process is exposed to the wet environment. The stability of the bearing allows the fabrication of combinatorial macro and micro dimension of free-form cylindrical components including traditional turning operations such as straight turning and contouring of variety shapes. The pulse-width-modulation (PWM) method is used for controlling the spindle speed that is driven by DC brushed electric motor. The proof is presented in Chapter 3 where it has covered all details of design, construction and performance evaluation experiment. The performance evaluation focuses on the straight shaft of micro-machining capability with achievable diameter as much as 0.2 mm with aspect ratio of 1000. Below 0.2 mm diameter, the part is burnt and bent by thermal stresses due to high energy density. The rational of positive aid of this design concept and proof of cutting capabilities have high potential in opening new possibilities for extraordinary geometrical features components production.

# ii. To identify the influences of process parameter on the surface roughness in micro-cylindrical components fabrication by hybrid WEDT

The fluctuation of arithmetic average surface roughness value is identified resulted by varying combination between machine electrical parameter, non-electrical parameter and rotary axis mechanism characteristics. The highly influenced parameter to the surface roughness has been successfully initiated by response surface methodology (RSM) according to statistical 95% confidence level. As sorted in descending order are rotational spindle speed, voltage open, pulse intensity and wire tension. The other parameters that marginally has less influence on the surface roughness as analysed by Taguchi orthogonal array (OA) method as sorted in descending order are stabilizer E, stabilizer B, spindle direction, wire speed, voltage gap, table feedrate and stabilizer A.

The effect of pulse intensity and voltage is directly proportional on surface roughness but not wire tension and rotational spindle speed which are inversely proportional to surface roughness. The surface roughness has statistical significance effects and decreases with the decrease of pulse intensity from 10 to 8 Notch, voltage from 8 to 6 Notch and increases the rotational spindle speed from 400 to 2400 rev/min, wire tension from 12.2 to 14.8 N. The RSM also has discovered the interaction between the parameters which possess statistical significant. The scientific work is focusing on clarifying the phenomenon of parameter newly investigated but possesses crucial impact to the surface roughness such as spindle direction of rotary axis mechanism, machine stabilizer type E, the interaction of wire tension to voltage and wire tension to rotational spindle speed.

A mathematical equation for response surface model is formulated to characterize the relationship between the process parameter and surface roughness. The model for surface roughness:

Ra = 4.623524 - 0.116865\*Intensity of Pulse - 0.740501\*Voltage + 0.407668\*Wire Tension + 0.000060\*Rotational Spindle Speed + 0.011378\*Intensity of Pulse\*Wire Tension - 0.007660\*Voltage\*Wire Tension - 0.000009\*Wire Tension\*Rotational Spindle Speed + 0.064613\*Voltage\*Voltage - 0.017389\*Wire Tension\*Wire Tension

The correlation for the suggested reduced quadratic model equation generated found has good estimation as indicated by adjusted R<sup>2</sup> and predicted R<sup>2</sup> as much as 0.957 and 0.916 respectively. The confirmatory experiment also has conducted and confirmed the great estimation between the prediction and actual experiment with the highest relative error among ten of the experiments as much as 4.499%. The relative error less than 10% exhibits that the estimated result of the surface roughness value possesses good accuracy in the experimental range studied. The topographies of the machine surface are being identified by Scanning Electron Microscopy and Alicona Infinite Focus Microscope. The macro-ridges are found embodying the effects of the parameters to surface of the machined components. Alicona Infinite Focus Microscope facilitates the occurrence of macro-ridges which is hardly identified by SEM micrograph. The machined parts surfaced are deteriorated accordingly to the violent energy density generated by high pulse intensity and voltage, low wire tension and spindle speed. The smooth surface is observed with sufficient energy density to erode the workpiece materials at high spindle speed and tension of electrode wire.

# iii. To establish the optimum process parameter in fabrication of micro-cylindrical components by hybrid WEDT.

The optimum process parameter for producing the lowest surface roughness value is generated by Design-Expert software through desirability approach. The parameter and its level namely pulse intensity of 8 Notch, wire tension of 14.8 Newton, voltage of 7 Notch and rotational spindle speed of 2390 rev/min. The prediction of Ra value as much as 4.26684  $\mu$ m and the experimental as much as 4.0143  $\mu$ m. The confirmatory experiment has found that the relative error of as much as 5.9% which has confirmed the great accuracy of the proposed optimum parameter that is still less than 10%. The optimized parameter comprises adequate energy density to erode the materials with less deteriorated machined surface as a result from shallow crater size and fine macro-ridges.

# 5.2 Recommendations for Future Work

Based on this present study, factors that are worth to be explored in the future comprise of the following recommendations:

- i. Optimization on material removal rate and roundness. These performance criterions are considered as important in parts fabrication. MRR focuses on the productivity and roundness considered as one of the surface quality in processes which have direct effects on cost, production lead time and quality of machined parts. In this research, it only focuses on surface roughness because during the screening stage, the surface roughness is chosen priority compared to the MRR. MRR possesses contradictory effects compared to surface roughness as well as it suggests different statistical significant on process parameter.
- ii. Explore the subsurface of the machined parts. The electrical discharge sparking process has actually altered the metallurgical structure and characteristics on the subsurface that is several thermally altered layered such as recast layer and heat-affected-zone. Both of these layers believed to carry the micro-cracks that could cause stress failures of safety critical fabrication parts. However, none of the literatures cover investigation on sub-surface for micro-cylindrical components that are machined by hybrid micro WEDT.
- iii. Develop the rotary axis mechanism for commercializing purpose that is suitable for most WEDM machine. To enable the science push innovation, the current rotary axis is required to upgrade for industrial application. The upgrade consideration should focus to meet all types of the existing WEDM machines either submersible or nonsubmersible.
- iv. Explore on slitting operation and free-form geometrical features. In this present study, the straight turning approach is investigated. However, apart from fabrication of straight shaft, nowadays the demand for variety and free-form shapes of miniature devices and components is increasing rapidly. Therefore, further investigation on other operations and shapes is important to meet the current demand. It is believed

that the optimum process parameter that has been suggested in this present study is unable to be used with other WEDT machining operations.



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## APPENDIX A

## **Rotary Axis Mechanism Drawing and Parts**





#### **APPENDIX B**

#### **Speed Controller Coding**

```
* This file provides the functions for the PWM module using PIC16F887 using timer2 and
* CCP2CON as pwm
** Cytron Technologies Sdn. Bhd.
********
           *******
                                                    ********************/
#include <htc.h>
#include "system.h"
#include "pwm.h"
                             *******
/**************
* PUBLIC FUNCTION: pwm_initialize
* PARAMETERS:
* ~ void
* RETURN:
* ~ void
* DESCRIPTIONS:
* Initialize the CCP2 module to operate in PWM mode.
*******
void pwm_initialize(void)
{
         UNIVERSITI TEKNIKAL MALAYSIA MEL
                                                    ΔΚΔ
     // Setting PWM frequency = 4.88khz, using PIC16F887 with 20MHz Crystal
     PR2 = 0xFF;
     T2CKPS1 = 0;
     T2CKPS0 = 1;
                // Timer 2 prescale = 4.
                      // Turn on Timer 2.
     TMR2ON = 1;
     CCP2M3 = 1;
     CCP2M2 = 1;
                      // Configure CCP2 module to operate in PWM mode.
     CCP2M1 = 0;
     CCP2M0 = 0;
     CCPR2L = 0x00;
}
* PUBLIC FUNCTION: pwm_set_duty_cycle
*
* PARAMETERS:
* ~ ui_duty_cycle
                - The duty cycle of the PWM, 10 bits.
```

```
* RETURN:
* ~ void
* DESCRIPTIONS:
* Set the duty cycle of the PWM.
void pwm_set_duty_cycle(unsigned int ui_duty_cycle)
{
     CCP2CON = (CCP2CON & 0b00001111) | (0b00110000 & ((unsigned char)(ui duty cycle
<< 4)));
     CCPR2L = ui duty cycle >> 2;
}
//======
        \parallel
     Author
                             : MUHAMMAD AKMAL BIN MOHD ZAKARIA
                             : SK40C WITH PIC16F887 (ROTARY ADAPTER)
     Project
\parallel
     Project description
                             : Driving DC brush motor with MD10C
\parallel
//
//======
\parallel
     include
_______
#include <htc.h>
#include "lcd.h"
#include "system.h"
#include "pwm.h"
// Configuration
_____
__CONFIG(HS &
                       // External Crystal at High Speed
            WDTDIS &
                            // Disable Watchdog Timer.
                             // Enable Power Up Timer.
          PWRTEN &
                             // Disable Brown Out Reset.
            BORDIS &
           MCLREN &
                             // MCLR function is enabled
            LVPDIS);
                             // Disable Low Voltage Programming.
//
     function prototype
void delay_ms(unsigned int ui_value);
void sign_magnitude_pwm(void);
void locked antip pwm(void);
void wait_sw1(void);
     main function
//
//=========
void main(void)
{
     PORTA = 0;
                                                    // Clear Port
     PORTB = 0;
     PORTC = 0;
     PORTD = 0;
     TRISA = 0b0000000;
                                              // set PORTA as OUTPUT
     TRISB = 0b00000111;
                                              // set PORTB<7:3> as OUTPUT ,
PORTB<2:0> as INPUT
     TRISC = 0b0000000;
                                              // set PORTC as OUTPUT
```

```
TRISD = 0b0000000;
                                          // set PORTD as OUTPUT
                                          // Set PORTA as Digital I/O
       ANSEL = 0;
       ANSELH = 0;
                                          // SET PORTB as DIGITAL I/O for PIC16F887
       lcd_initialize();
                                                 // Initialise LCD
                                                 // Initialise PWM1
       pwm_initialize();
unsigned char mode = 1;
while (1)
       {
       switch (mode)
              {
              case 1: while (SW1 == 1)
                                   {
                                   lcd clear();
                                   lcd_putstr("WELCOME TO\nUTEMEX 2016");
                                   wait_sw1();
                                   if(SW1 == 0) break;
                                   lcd_clear();
                                   lcd_putstr("ROTARY ADAPTER\nSPEED CONTROLLER");
                                   wait sw1();
                                   if(SW1 == 0) break;
                                   lcd clear();
                                   lcd_putstr("Press RUN when\nReady");
                                   wait sw1();
                                   }
                            while (SW1 == 0);
                            locked antip pwm();
                            pwm_set_duty_cycle(0);
                            DIR = 0;
                            break;
                             TEKNIKA
                                          // if SW1 is press, increase the mode number
       if (++mode > 2)
until it is max and loop back
              {
              mode = 1;
              }
/***********
                                              ******
* PRIVATE FUNCTION: locked_antip_pwm
** PARAMETERS:
* ~ void
** RETURN:
* ~ void
** DESCRIPTIONS:
* MD10C Locked Anti-Phase PWM mode
     *****
                         ******
                                                              ****************************/
void locked antip pwm (void)
{
unsigned int speed;
lcd_clear();
lcd_home();
                                         172
```

```
lcd_putstr("DIR:");
lcd_goto(0x07);
lcd_putstr("PWM:");
lcd_2ndline();
lcd_putstr("Locked-Antip PWM");
            lcd_goto(0x04);
            lcd_putstr("1");
            DIR = 1;
            for (speed=740; speed=740; speed--)
                   {
                   delay_ms(10);
                   pwm_set_duty_cycle(speed);
                   lcd goto(0xB);
                   lcd bcd(4,speed);
                   }
/***************
                  ***
                                  **************
* PRIVATE FUNCTION: delay_ms
* PARAMETERS:
* ~ ui_value
            - The period for the delay in miliseconds.
* RETURN:
* ~ void
* DESCRIPTIONS:
* Delay in miliseconds.
                                                                      ******/
void delay_ms(unsigned int ui_value)
{
      while (ui_value-- > 0) {
                             // macro from HI-TECH compiler which will generate 1ms
            delay_ms(1);
delay base on value of _XTAL_FREQ in system.h
      }
/*********
              ******
                            EKNIKAL MALAYSIA MELAKA
* PRIVATE FUNCTION: wait sw1
* PARAMETERS:
* ~ void
* RETURN:
* ~ void
* DESCRIPTIONS:
* wait for switch 1 to be press while have delay
             void wait_sw1(void)
{
      unsigned char i;
      for (i = 0; i < 200; i++)
            {
                   if (SW1 == 0)
                   {
                         return;
                   delay_ms(10);
```

## **APPENDIX C**

## Geometrical Features of WEDT Micro-machining







### **APPENDIX D**

## Datasheet of Titanium Ti6Al4V



		. G. V. J. J.
	UNIVERSITI TEKNIKAL MA	LAYSIA MELAKA
Category	Titanium Alloy	
Class	Warran	
Class	wrought	

Type Alpha-beta alloy

Designations United States: ASTM B265 Grade5, ASTM B348 Grade5, ASTM B381 Grade5, MIL-T-9046, MII

Grade 5 titanium is the workhorse of all the titanium grades. It is also known as Ti-6AL-4V or simply Ti 6-4. Its hig

#### **Market Applications**

Aerospace, Medical, Marine, Chemical Processing

#### **Physical Properties**

Table 1. Typical physical properties for Ti6Al4V.

#### Property

Density g/cm <sup>3</sup> (lb/ cu in)
Melting Range °C±15°C (°F)
Specific Heat J/kg.°C (BTU/lb/°F)
Volume Electrical Resistivity ohm.cm (ohm.in)
Thermal Conductivity W/m.K (BTU/ft.h.°F)
Mean Co-Efficient of Thermal Expansion 0-100°C /°C (0-212°F /°F)
Mean Co-Efficient of Thermal Expansion 0-300°C /°C (0-572°F /°F)
Beta Transus °C±15°C (°F)

#### **Mechanical Properties**

Table 2. Typical mechanical properties for Ti6Al4V.

Property
Tensile Strength MPa (ksi)
0.2% Proof Stress MPa (ksi)
Elongation Over 2 Inches %
Reduction in Area %
Elastic Modulus GPa (Msi)
Hardness Rockwell C
Specified Bend Radius <0.070 in x Thickness
Specified Bend Radius >0.070 in x Thickness
Welded Bend Radius x Thickness
Charpy, V-Notch Impact J (ft.lbf)

#### Fabrication

Weldability - Fair

Forging – Rough 982°C (1800°F), finish 968°C (1775°F)

Annealing - 732°C (1350°F), 4hr, FC to 566°C (1050°F), A.C. F.C. not necessary for bars

Solution Heat Treating - Forgings

Ageing – 904-954°C (1660-1750°F), 5 min-2hrs, W.Q. 538°C (1000°F), 4hr, A.C.

## **APPENDIX E**

## Approach for Optimization

## First Step

			Lower	Upper	Lower	Upper		
	Name	Goal	Limit	Limit	Weight	Weight	Importance	
	ntensity of Pı	is in range	8	10	1	1	3	
	Voltage	is in range	6	8	1	1	3	
\	Vire Tension	is in range	12.2	14.8	1	1	3	
F	Rotational Sp	is in range	400	2400	1	1	3	
F	Ra garage	minimize	4.27667	4.672	1		3	
	Number I	ntensity of P	Voltage Wir	re TensiorRo	otational S <sub>I</sub>	Ra	Desirability	
	1	8.20	6.77	14.77	2344.93	4.27545	1.000	
	2	VND 8.28	6.53	14.78	2396.11	4.27273	1.000	
	3	8.35	6.77	14.80	2396.27	4.27627	1.000	
	-12	8.20	6.77	14.75	2346.64	4.27622	1.000	
	5	8.12	6.70	14.78	2348.17	4.26839	1.000	
	11116/	8.08	6.70	14.78	2245.14	4.27469	1.000	
	7	8.27	6.64	14.78	2350.93	4.27547	1.000	
	8	8.02	6.76	14.60	2393.58	4.27646	1.000	
	9	8.14	6.44	14.76	2311.83	4.2755	1.000	
	10	8.11	6.50	14.72	2319.07	4.27564	1.000	
	11	8.26	6.76	14.77	2366.94	4.27618	1.000	
	12	8.02	6.12	14.79	2397.91	4.2734	1.000	
	13	<u>8.14</u>	<u>6.53</u>	<u>14.79</u>	<u>2360.00</u>	4.26763	<u>1.000</u>	Selecter
	14	8.01	6.32	14.70	2400.00	4.27089	1.000	
	15	8.14	6.63	14.70	2368.45	4.27402	1.000	
	16	8.00	6.05	14.80	2393.83	4.27654	1.000	
	17	8.17	6.56	14.72	2359.24	4.27441	1.000	

		Lower	Upper	Lower	Upper		
Name	Goal	Limit	Limit	Weight	Weight	Importance	
Intensity of Pri	is target = 8.1	8	10	1	1	3	
Voltage	is in range	6	8	1	1	3	
Wire Tension	is in range	12.2	14.8	1	1	3	
Rotational Sp	is in range	400	2400	1	1	3	
Ra	minimize	4.27667	4.672	1	1	3	
Solutions							
Number I	ntensity of P	Voltage Wi	re TensiorRo	otational S	Ra	Desirability	
1	8.00	6.23	14.67	2399.46	4.27646	1.000	
2	8.00	6.54	14.69	2333.49	4.27135	1.000	
3	8.00	6.36	14.70	2396.54	4.26911	1.000	
4	8.00	6.06	14.79	2399.79	4.2766	1.000	
5	8.00	6.54	14.77	2274.31	4.26898	1.000	
6	8.00	6.91	14.76	2292.11	4.27341	1.000	
7	<u>8.00</u>	<u>6.71</u>	<u>14.70</u>	<u>2364.80</u>	4.26804	<u>1.000</u>	Selected
8	8.00	6.92	14.74	2316.15	4.2743	1.000	
9	8.00	6.95	14.68	2377.05	4.27567	1.000	
10	8.00	6.84	14.62	2392.15	4.27609	1.000	

## Second Step ALAYSIA

	S	100	Lower	Upper	Lower	Upper	-	
	Name	Goal	Limit	Limit	Weight	Weight	Importance	
	Intensity of Pi	is target = 8.00	8	10	1	1	3	
	Voltage	is in range	6	8	1	1	3	
	Wire Tension	is equal to 14.80	12.2	14.8	1	1	3	
	Rotational Sp	is in range	400	2400	1	1	3	
-	Ra	minimize	4.27667	4.672	1	1	3	
	Solutions	1 1						
	Number	Intensity of Pulse	Voltage	Wire Tension	Rotational S	Ra	Desirability	
		8.00	6.55	14.80	2153.56	4.27514	1.000	2'
	2	8.00	6.63	14.80	2321.29	4.26216	1.000	
	UNI¥E	ERSITI 8.00 8.00	6.86 6.30	(A) <sup>14.80</sup> 14.80	2255.95 2343.39	4.27115 4.26652	1.000 1.000	(A
	5	8.00	7.15	14.80	2382.01	4.27628	1.000	
	6	8.00	6.75	14.80	2345.42	4.26165	1.000	
	7	8.00	6.79	14.80	2219.90	4.27203	1.000	
	8	8.00	6.93	14.80	2342.37	4.26717	1.000	
	9	8.00	6.65	14.80	2325.06	4.26199	1.000	
	10	8.00	6.58	14.80	2183.46	4.27272	1.000	
	11	8.00	6.30	14.80	2255.12	4.27343	1.000	
	12	8.00	6.48	14.80	2178.29	4.27411	1.000	
	13	8.00	6.80	14.80	2222.01	4.27208	1.000	
	14	8.00	6.05	14.80	2392.40	4.27651	1.000	
	15	8.00	6.52	14.80	2255.51	4.2676	1.000	
	16	<u>8.00</u>	<u>6.51</u>	<u>14.80</u>	2390.87	<u>4.25749</u>	<u>1.000</u>	Selected
_	17	8.00	6.80	14.80	2241.87	4.27067	1.000	
	18	8.00	6.81	14.80	2195.10	4.27442	1.000	
	19	8.00	6.92	14.80	2291.06	4.27067	1.000	
	20	8.00	6.34	14.80	2197.86	4.27631	1.000	
	21	8.00	7.11	14.80	2364.45	4.27483	1.000	
	22	8.00	7.02	14.80	2367.75	4.26933	1.000	
	23	8.00	7.07	14.80	2321.23	4.27609	1.000	
	24	8.00	6.48	14.80	2247.71	4.26873	1.000	

### Third Step

		Lower	Upper	Lower	Upper		
Name	Goal	Limit	Limit	Weight	Weight	Importance	
Intensity of Pi	is target = 8.00	8	10	1	1	3	
Voltage	is target = 7.00	6	8	1	1	3	
Wire Tension	is equal to 14.80	12.2	14.8	1	1	3	
Rotational Sp	is in range	400	2400	1	1	3	
Ra	minimize	4.27667	4.672	1	1	3	
Solutions							
Number	Intensity of Pulse	Voltage Wi	ire TensiorRe	otational S	Ra	Desirability	
1	8.00	7.00	14.80	2295.57	4.27405	1.000	
2	8.00	7.00	14.80	2332.71	4.27121	1.000	
3	8.00	7.00	14.80	2263.46	4.2765	1.000	
4	8.00	7.00	14.80	2276.92	4.27547	1.000	
5	<u>8.00</u>	<u>7.00</u>	<u>14.80</u>	<u>2388.29</u>	<u>4.26697</u>	<u>1.000</u>	Selected
6	8.00	7.00	14.80	2354.46	4.26955	1.000	
7	8.00	7.00	14.80	2304.42	4.27338	1.000	
8	8.01	7.00	14.80	2267.06	4.27666	0.999	
9	8.02	7.00	14.80	2275.45	4.27663	0.997	
10	8.00	7.00	14.80	2142.17	4.28576	0.992	
11	8.00	6.96	14.80	2239.00	4.27666	0.988	
12	8.00	7.00	14.80	1946.35	4.30072	0.979	
13	8.00	7.00	14.80	1118.96	4.3639	0.920	
14	8.00	7.00	14.80	609.75	4.40279	0.880	
E							
14 Solutions fo	und Armo						

# Fourth Step

....

Name	Goal	Limit	Limit	Weight	Weight Im	portance	
Intensity of Pi	is target = 8.00	8	10	1	1	3	
Voltage	is target = 7.00	6	8	1	1	3	
Wire Tension	is equal to 14.80	12.2	14.8	1	1	3	
Rotational Sp	is target = 2390.00	400	2400	1	1	3	
Ra	minimize	4.27667	4.672	1	1	3	
Solutions Number	Intensity of Pulse	Voltage Wi	re TensiorR	otational Su	Ra De	sirability	
Solutions Number 1	Intensity of Pulse 8.00	Voltage Wi <u>7.00</u>	re TensiorRo <u>14.80</u>	otational S <sub>I</sub> 2390.00	Ra De	esirability <u>1.000</u>	Selected
Solutions Number 1 2	Intensity of Pulse 8.00 8.01	Voltage Wi <u>7.00</u> 7.00	re TensiorRo <u>14.80</u> 14.80	otational S <sub>I</sub> <u>2390.00</u> 2390.00	Ra De 4.26684 4.26745	esirability <u>1.000</u> 0.999	Selected
Solutions Number 1 2 3	Intensity of Pulse <u>8.00</u> 8.01 8.00	Voltage Wi 7.00 7.00 6.99	re TensiorRo <u>14.80</u> 14.80 14.80	<b>otational S<sub>I</sub></b> 2390.00 2390.00 2390.00	Ra         De           4.26684	esirability <u>1.000</u> 0.999 0.997	Selected
Solutions Number 1 2 3 4	Intensity of Pulse <u>8.00</u> 8.01 8.00 8.00	Voltage Wi 7.00 6.99 7.00	re TensiorRo <u>14.80</u> 14.80 14.80 14.80	2390.00 2390.00 2390.00 2390.00 2353.74	Ra         De           4.26684	esirability <u>1.000</u> 0.999 0.997 0.995	Selected

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