COST ANALYSIS AND PERFORMANCE OPTIMIZATION OF WIRE-EDM AS ALTERNATIVE TO PRODUCT PROTOTYPING FOR THE HARD-TO-MACHINE BASED MATERIAL

BY

MAKBUL HAJAD

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF MASTER OF
ENGINEERING (LOGISTICS AND SUPPLY CHAIN SYSTEMS
ENGINEERING)
SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY
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A Thesis Presented

By

MAKBUL HAJAD

Submitted to

Sirindhorn International Institute of Technology

Thammasat University

In partial fulfillment of the requirements for the degree of

MASTER OF ENGINEERING (LOGISTICS AND SUPPLY CHAIN SYSTEMS ENGINEERING)

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JUNE 2017

Acknowledgements

I would like to extend the deepest appreciations to the peoples and institutions that have given much contributions and supports that enable me to accomplish this master degree dream.

First of all, I would like to deliver my sincere honors and appreciations to my advisor Asst. Prof. Dr. Suchada Rianmora for every valuable suggest and guidance, constructive advice and motivation for me during my thesis work. Without her effort and support I would not be sure to complete and finish this thesis work

Second, I would like to thank to my committee members, Assoc. prof. Dr. Pisal Yanradee, Assoc. Prof. Dr. Huynh Trung Luong, and Asst. Prof. Dr. Viboon Tangwarodomnukun, for their encouragement, insightful comments, and precious suggestions which academically support me and complement my thesis paper.

Third, I would like to gratefully thank to Sirindhorn International Institute of Technology-Thammasat University, which has provided me a financial support through graduate scholarship of excellent foreign students (EFS) program that enable me to pursue and complete my master degree.

I further extend my personal gratitude and love to my wife (Ayu Kusuma Wardani) and lovely daughter (Araya Alianannaura Makbul) for being my greatest motivation, faithfully accompanying me during the hard period of master study, and provide much support and love.

Finally, I would like to thank to my beloved and proud father and mother and all families for continuously supporting, loving, caring and encouraging me throughout all my studies at SIIT. And last but not the least, I want thank to my best friends for always being there for me through good times and bad times until we accomplished this master study together.

ABSTRACT

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Wire-EDMing operation was a well-known advanced machining technology due to its ability to cut the hard materials. The wire-EDM can provide a very good surface cut with high cutting accuracy. It has been used in various industrial applications such as aerospace industry, mobile industry and surgical tool industry. Due to the complexity and stochastic machining process, the performance of the wire-EDM is based on the proper selection of the machining parameters. This study aimed to investigate the effect of machining parameters such as servo voltage, pulse on time, pulse off time, wire feed and wire tension on the output performance namely machining cost, MRR, surface roughness and machining accuracy. Taguchi’s utility concept was utilized to perform the multiple objective optimization in order to obtain the optimal setup of wire-EDMing parameters with respect to the interested outputs. In order to reduce the machining cost, an investigation of multiple layer cutting strategy was provided, including the output comparison between the single layer case and multiple layer case. Moreover, an investigation of wire-EDMing characteristics on machining the multi-contour part also provided with the two different case study. Finally, a micrograph analysis was added to clearly visualize the machining parameters effect on the cut quality.

Keywords: *Wire-EDM cost analysis, multi-objective optimization, Taguchi’ Utility concept, Multiple layer cut*.

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Chapter 1
Introduction

1.1 Background of the study

The competitiveness of today business has forced manufacturer to turn into an efficiently continuous innovation. Nowadays, the customers require manufacturer to much more update of the characteristic or even the quality of the product. In another mean, the manufacturer therefore needs to respond that mentioned demand behavior through the sustainable product development. This happened naturally, and the sustainability of a product will be based on the interaction between customer and manufacturer. In term of product development, there always a high possibility for the proposed product design to weather meet the costumer expectation or not. It is often that the new product has an unpredicted problem. Therefore, a prototyping is used as the part of product development process to give opportunity for the designers to explore the alternatives design, test theorem, and testing the performance of the product sample before starting the mass production of new product design.

Advanced machining technology equipped with Computer Numerical Controller (CNC), basically, is adopted by the manufacturers; especially for whose product are based on the hard-to-machining materials such as titanium, ceramics, zirconium, steel, carbides or many others high strength temperature resistance alloys. Since the conventional machining technologies tend to reach their limitation when dealing with the hard-to-machine material, consequently, the advanced machining technology is chosen instead of conventional one. This was due to the requirement of the high precision product, high cut quality, and the high production rate. Also, the utilization of these advanced machining technology were considered as the long term solution in relation to reducing the production cost and eliminate the manpower error.

There are several options used widely in metal manufacturing process such as *Electrical Discharge Machine* (EDM) laser beam machine, waterjet machine and chemical machine. However, the appropriate option will be based on material characteristic and the requirement of the finish product specification, for example, the waterjet machine (WJM) as it is usually used for the rough cutting process for hard-to-cut material. Moreover, laser beam machine (LBM) cutting technique is used widely for cutting conductive material which is using the high temperature to cut the unwanted material from the workpiece in high cutting rate. In additional, EDM especially wire-EDM as non-traditional cutting technique, it provides good surface quality of end product due to the nature of the process, which the material is cut by the thermal energy without any contact between the wire and material. Thus, it reduces the stress and heat effect on the cut surface, providing the high-quality surface.

Wire-EDM has been a dominant technology for cutting the complicated shape and difficult-to-machine materials, which are widely used in tooling that requiring high surface integrity and accuracy. Thus, it has been valuable technology for manufacturer involving for the stamping die, extraction dies and prototype parts (Kozak, *et al.*, 2004). As an advanced machining, wire-EDM removes the unwanted part of material using the thermal energy obtained from the repeated discharges current produced between the wire and the workpiece in the ionized water called dielectric fluid (Sommer, 1998). Wire-EDM is generally utilized for cutting a tough materials such as metal, steels and carbides. Also it was commonly used for finishing parts at the aerospace, automotive, and surgical component industry. Moreover, it also can be used for producing the intricate shapes even a small diameter holes, which are impossible to be machined by using traditional machining technology. However, as a costly process, normally the engineer implement the stacking or multi-layer cutting technique in their machining process of wire-EDM in order to obtain higher machining efficiency. Where the materials are constructed in multi-layers which can give multi product in one cutting process. It aims to reduce the production time with the increase in productivity. To construct the tool path and reduce the machining error, the wire EDM normally equipped with the CNC technology which may ease the machining operation. In addition, Wire-EDM allows the engineer to cut the material up to 300 mm of thickness of the material (Sommer, 1998).

1.2 Problem statement

For making the prototype from the hard-to-machine material, wire-EDM has several advantages such as the ability to cut the complex and difficult shape product with promising the high accuracy, good surface quality, and appropriateness for cutting the hard and strength material. However, it was also well known as costly and low cutting speed technology. Thus, these condition has limited the used of wire-EDM in the worldwide industry. Moreover, the wire EDM also was very stochastic operation, improper selection of the machining factors can cause a very serious consequences such as wire breakage and short-circuiting, reducing the speed and also productivity. Although, many researchers have been involved widely in the investigation of wire EDM performance, while very limited studies investigate the wire-EDMing optimization process considering machining cost as the output performance in the multi-layer cutting strategy in order to reduce the machining cost and increase the machining productivity with the acceptable machining performance.

1.3 Objectives of the study

The objective of this research are described as follow:

1. To implement the multi-layer cutting strategy on wire-EDMing operation of the steel material in order to reduce the machining cost and increase the MRR with the acceptable cut quality.
2. To Analyze and compare the machining cost of wire-EDMing operation for both the single and multiple layer cutting condition.
3. To conduct the multiple objectives optimization on the wire-EDMing operation considering the input parameters (servo voltage, pulse on time, pulse off time, wire feed and wire tension) based on the machining performance, namely machining cost, MRR, accuracy and surface roughness.

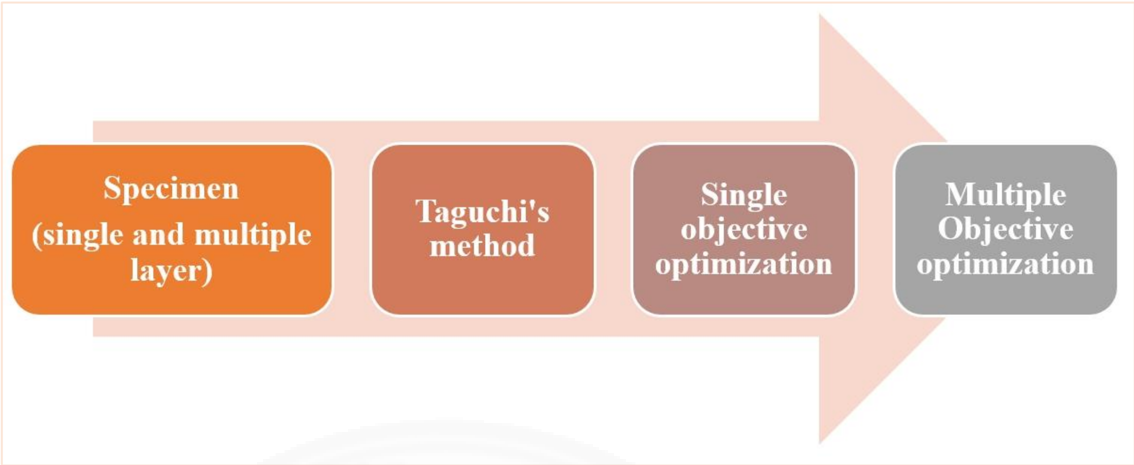


Figure 1.1 Overview of the researches

1.4 Addressed Issues

To accomplish the research objective, the following issues are addressed:

1.4. 1 The contribution of the selected machining parameters

Improper parameter selection in wire-EDMing process may reduce the performance of wire-EDMing operation. It gives not only an insufficient cutting performance but also may contribute to the wire rupture and shorting electrical current. Better understanding of the nature of each parameter on every single response variable may give the better machine adjustment. Moreover, adequately adjust the cutting parameters may give the not only a higher performance of the machine, but also can give a higher efficiency of the machine usage.

1.4. 2 The optimum set of cutting parameters which respect to all responses

As a random and stochastic operation, each machining parameter of wire-EDMing may give different effect on a single response. For example, a higher pulse duration may give higher cutting rate and MRR, however, it contributes to making the crater on the cut surface and lower accuracy. The cutting parameters, therefore, need to be adjusted where all interested response are considered. A multiple objective optimization technique by using utility concept is provided in the present study in order to achieve a better machining performance of wire-EDM

1.4. 3 The effect of multiple layer and multi-angle contour on cutting process

A high machining cost is required in wire-EDMing operation. Thus, an effective cutting process is essential for wire-EDMing operation. A multi-layer cutting strategy therefore is utilized in this study to achieve a higher machining efficiency. However, the effects of this strategy on other response therefore are need to be analyzed in order to avoid the unexpected results. Moreover, the multi-angle contour also such a great issue in wire-EDMing operation, since it may effects the cutting rate and other machining output.

1.5 Scopes and limitations of the study

Scopes of this study as follows:

(1) The multiple layer cutting strategy has been applied to increase the machining performance while reducing the production cost

(2) The effect of the selected machining parameters on the machining cost, MRR, surface roughness and accuracy were investigated.

(3) Both single objective optimization and multiple objective optimization were investigated to give better performance of the wire EDM characteristics.

(4) The validation experiment was constructed to find out the comparison between the predicted result and validation result. Also, the comparison between the initial parameters (based on machine manual book) and optimized parameters was provided.

(5) The micrograph analysis is conducted to visualize the effect of the selected parameters on the cut surface.

Limitations of this study as follow:

(1) The shape of proposed product to be produced is limited with 2D dimension according to wire-EDM limitation.
(2) The selected parameters to be investigated limited with Pulse on, Pulse off, servo voltage, wire feed and wire tension.
(3) The performance of the machining process was limited based on machining cost, MRR, surface roughness, machining accuracy and micrograph surface.

1.6 Organization of the thesis

The thesis can be organized as follows:

Chapter 1 presents the study background, problem statement, objective, the addressed issues, scope and limitation and thesis organization.

Chapter 2 reviews the related works including the advanced machining technology, wire-EDM operation, parameters effect, response of interest and wire-EDM assisting technique along with the gap found from the reviewed literatures.

Chapter 3 addresses about the design and methodology including the machining setup, materials used, measurement and analysis method.

Chapter 4 presents the results and findings from the experimental works. Also, a deep discussion according to the result and a brief comparison with the existing work.

Chapter 5 describes the obtained conclusion from the experimental work and proposed recommendations for future improvements.

Chapter 2
Literature Review

Many researchers had been involved in the investigation of the wire-EDMing process including wire-EDMing parameter, performance optimization, and also the wire-EDMing assisting techniques in order to achieve the higher performance of the wire-EDMing operation. The wire-EDMing also had been proposed for machining several materials such as steel, titanium, and ceramic, carbide, etc. In this chapter, the introduction of the wire-EDMing process was discussed deeply including the machining process, component and influences, and the machining parameters along with the output of interest. Moreover, the past researches of wire-EDMing which had been conducted were also investigated to find the gap study and solve the problem which has been described in the chapter before.

2. 1 Advanced machining technology

Currently, the machining technology has been classified into two major types: 1) conventional machining and 2) advanced machining technology. Conventional machining technology normally used the cutting tool with a certain specification to cut the workpiece. The cutting tool needs to be harder than the workpiece to be machined, therefore the unwanted material can be removed from the workpiece. The cutting tool also should make contact and penetrate into the workpiece in a particular depth and move through the contour path according to the desired shape. If there any of this element are absence in a machining technology, such as the contact between the cutting tool and workpiece or any motion, therefore it called non-conventional machining technology or advanced machining technology (El-Hofy, 1998).

Advanced machining technology has been used widely in the sophisticated manufacturing industries due to the ability to machine the hard and tough material. There are several advanced machining technologies proposed earlier, according to the power used for material removing, it is classified into 3 main parties: (1) mechanical, (2) thermal and (3) chemical and electrochemical (Figure 2.1). These advanced machining technologies had the difference in material removal mechanism, system component, process parameters, characteristic and applications (El-Hofy, 1998).

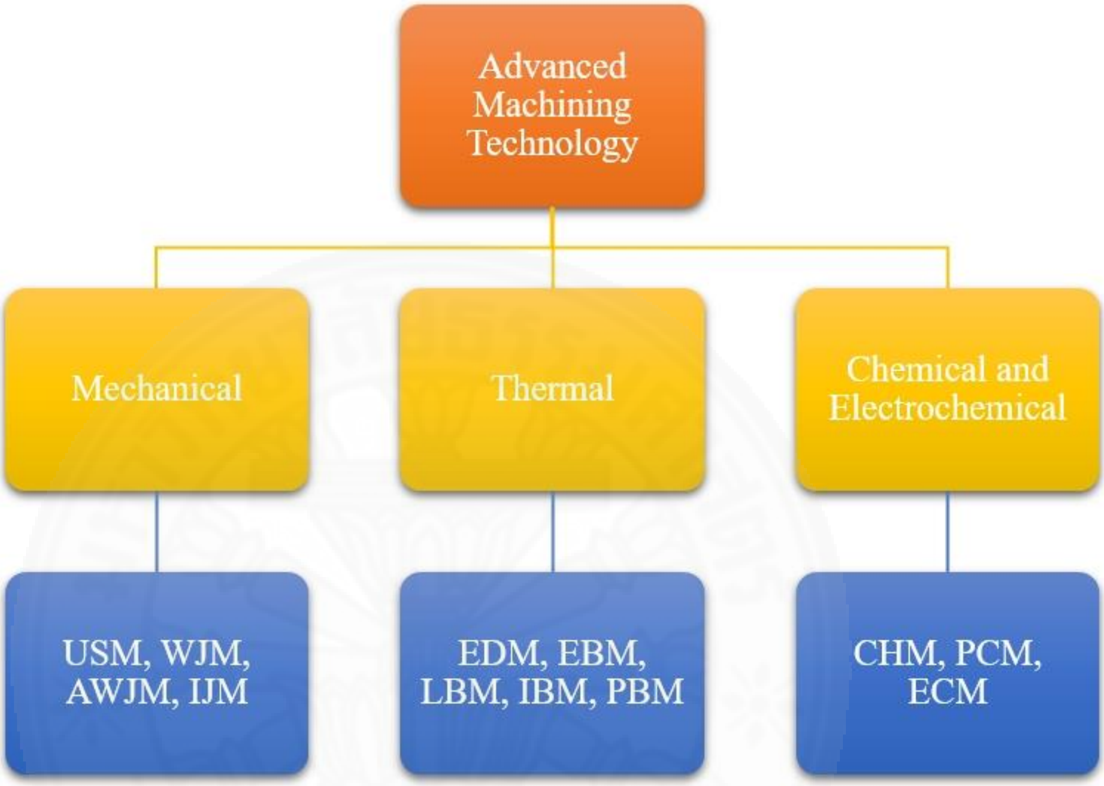


Figure 2.1 Advanced machining technology classification (El-Hofy, 1998)

2. 2 Electrical Discharge Machining (EDM)

One of the popular advanced cutting technology used in worldwide industry is EDM. The principle was to use the thermal energy gained from the repeated electrical discharge between two material (electrode and workpiece) to melt and remove the unwanted material with the assisting of dielectric fluid. This thermal energy was used for obtaining the high-precision machining process with a fine surface cut and controlled current. In EDM process, the tool electrode was moved toward the workpiece resulting in a very small gap between the electrode and workpiece so that an impressed voltage was sufficient to ionizing the dielectric. A very short discharge period resulted in the dielectric space, which separating the wire and workpiece. Therefore, this thermal energy resulted from the discharge current remove the material from the workpiece. Moreover, there was no directly contact between the wire and workpiece which may reduce the vibration, mechanical stresses, and crater issues during the cutting process (Ho and Newman, 2003).

2. 3 Wire-EDM machining process

Wire EDM used the wire that travels toward the workpiece to erode the material. This electrode was normally made from brass, tungsten or copper of 0.05 mm – 0.3 mm diameter, allow it to gain a small kerf. The tension of wire electrode is maintained to be constant using a certain device to reduce the inaccuracy of the result (Hardik A. Petel, 2015). The electrode, therefore, is precisely controlled using a certain CNC system (Figure 2.2) in order to assure movement of wire in line with the contour path. In the wire-EDMing process, the material was removed by the electricity by means of spark erosion. The spark was generated between two materials (electrode and workpiece), the sparks therefore transformed into the thermal energy with a range of 8000 to 12000 ^{o}C at a pulsating direct current supply of 20000 to 30000 Hz (Abulais, 2014), by means the material should be conductive in order to be wire-EDMed (Sommer, 1998).

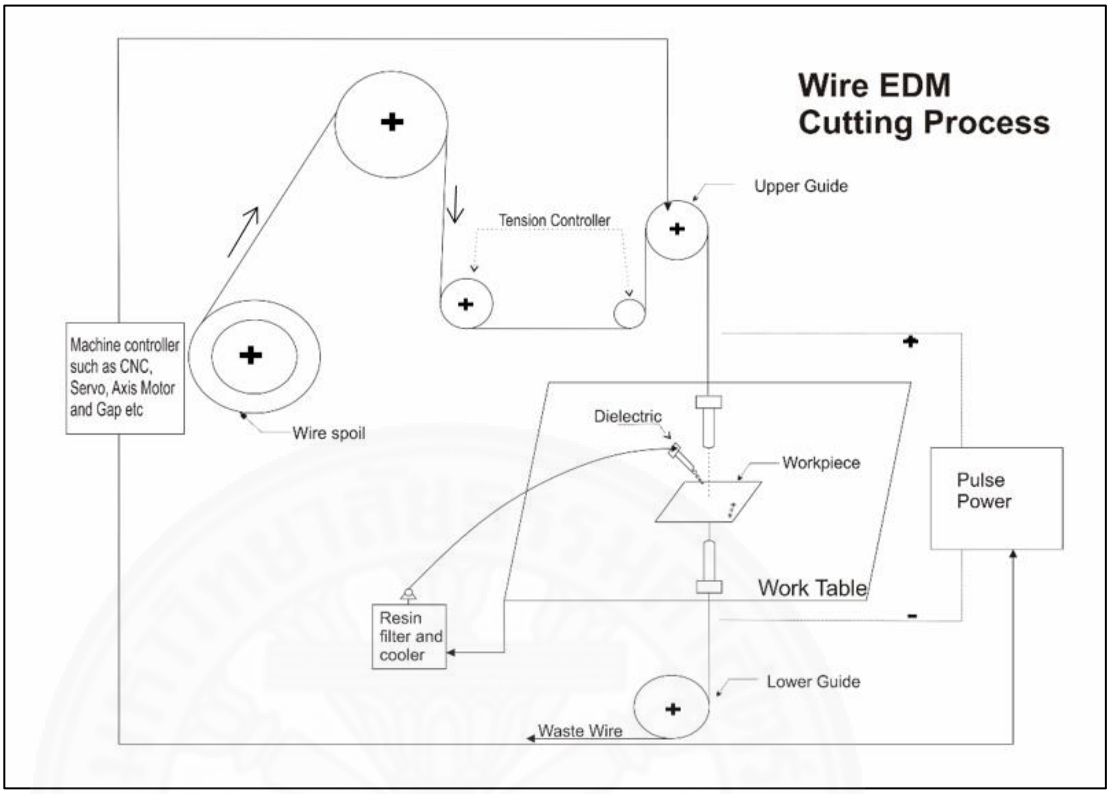


Figure 2.2 Wire-EDM process mechanism

Between the wire and the workpiece, there is a small gap controlled and maintain through a DC (Direct Current) and AC (Alternating Current) system, with the gap range from 0.051 mm to 0.076 mm. The servo-mechanism system also prevent the wire electrode of being shorting out against the workpiece and directs the wire as it move toward the expected path (Figure 2.3) (Sommer, 1998).

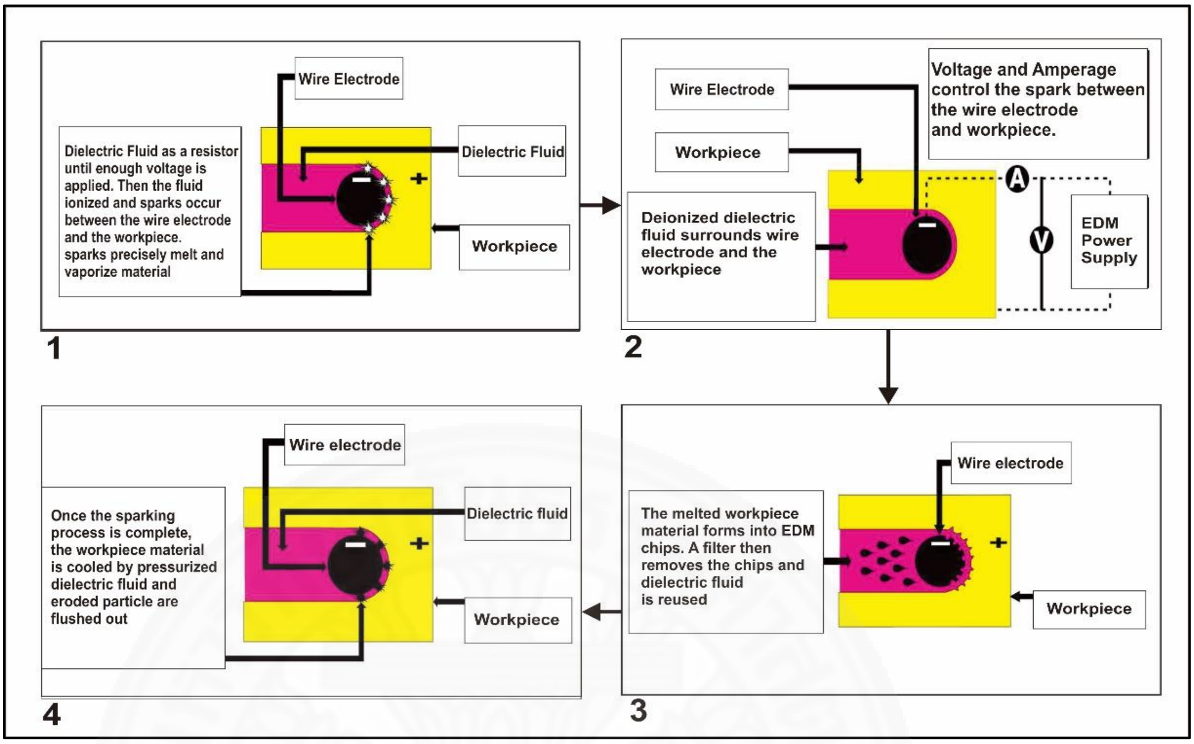


Figure 2.3 Wire EDM erosion process (Sommer, 1998)

2. 4 Wire-EDM components and influences

The selection of machining parameters of Wire-EDMing process was random and stochastic process, its influence greatly in the machining performance. Improperly selected parameters may cause wire breaks and short electrical circuits problems, and many others unexpected problem (Ho and Newman, 2003). There are several parameters may determine the performance of wire-EDM process such as:

2.4. 1 Wire electrode

A wire electrode is a tool used in wire-EDMing but there was no contact with the material being cut. There must be enough space between the electrode and material that filled with the ionized fluid called dielectric, which also runs as the insulator, cooler, and flusher for the work material during the cutting process. The selection of the wire properties normally depends on the work material. However, the material of wire needs to be electrically conductive, with a certain mechanical properties (tensile strength, elongation etc.). Basically, copper, brass and coated wire and fine wire (molybdenum and tungsten), utilized as the wire electrode with 0.02 mm to 0.30 mm of thickness (Kapoor, et al., 2010).

According to Jatinder et al. (2010), the wire conductivity was such a great importance for wire-EDMing process. The higher the conductivity, the more current could be supplied to the process, which means it may increase the spark and results in the higher cutting speed. The wire mechanical properties will influence greatly in the feasibility of the wire to be used in certain tension and wire vibration.

2.4. 2 Electrical power unit as the sparking generator

According to Richard (2007), the electrical pulse (as shown in Figure 2.4) with the magnitude of 20 V to 120 V and frequency on 5 kHz was occurred during the sparking process between the wire and work material, with 0.01 mm up to 0.15 mm gap. The system controls the pulse through adjustment the on-time, off-time and amperage that supplied to the wire during the cutting process. One cycle has consisted of one on-time and one off-time. Moreover, the cycle time is measured in microseconds (μ sec).

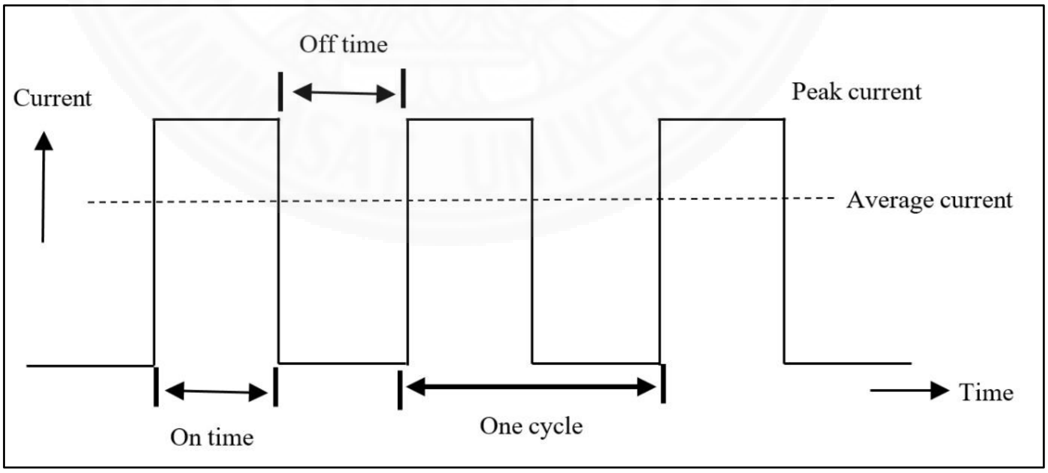


Figure 2.4 Train controlling for pulse generator in EDM (Stephenson, 2007)

The on-time or pulse on or pulse duration as referred to the time consumed for the current is turned on during the cut process. Then, it increases the voltage and the spark jumped from the wire into the workpiece, and when the wire and workpiece are connected with the spark, the voltage decreases and the amperage increases. The material, therefore, is melted and vaporized. At the same time, the dielectric water cools the eroded material and flush it away from the workpiece. At this point, the power was turned off, so was called the pulse off-time periods or pulse interval. The gap between the wire and the workpiece such an important factor in order to achieve the surface finish result. Because it will define the amount of spark (power) achieved by the workpiece. In wire-EDMing system, the gap between the wire and workpiece is controlled through servo voltage (SV). Then, it will also determine the kerf along the contour path (Khanduja and Mahesh, 2015).

2.4. 3 Dielectric fluid

According to Stephenson (2007), there are several functions of dielectric fluids such as:

a. As the insulators during the sparking process, to focus the electrical transfer along the wire EDM process. Means, the conductivity and the pressure of the dielectric need to be maintained at certain condition.
b. As the cooling agent for both the wire and the work material, that causes the temperature of the dielectric need to be maintained.
c. To solidify the surface of the work material being cut, therefore, the dielectric need to be circulated and filtered.
d. To flush away the eroded material out from the sparking area.

2. 5 Wire-EDM parameters and performances

There are several machining performances are considered widely in the wire EDM process namely, the cutting speed, kerf width, wire wear ration, accuracy (dimensional deviation), MRR and surface roughness (Figure 2.5). In order to achieve these expected performances, several parameters need to be adjusted namely pulse on/ff time, servo voltage, wire tension, wire feed, dielectric pressure and etc. However, those parameters give different effect on the machining performance, resulting the difficulty to cover all the expected performance in one setup parameters, also the machining performance are conflicting in nature.

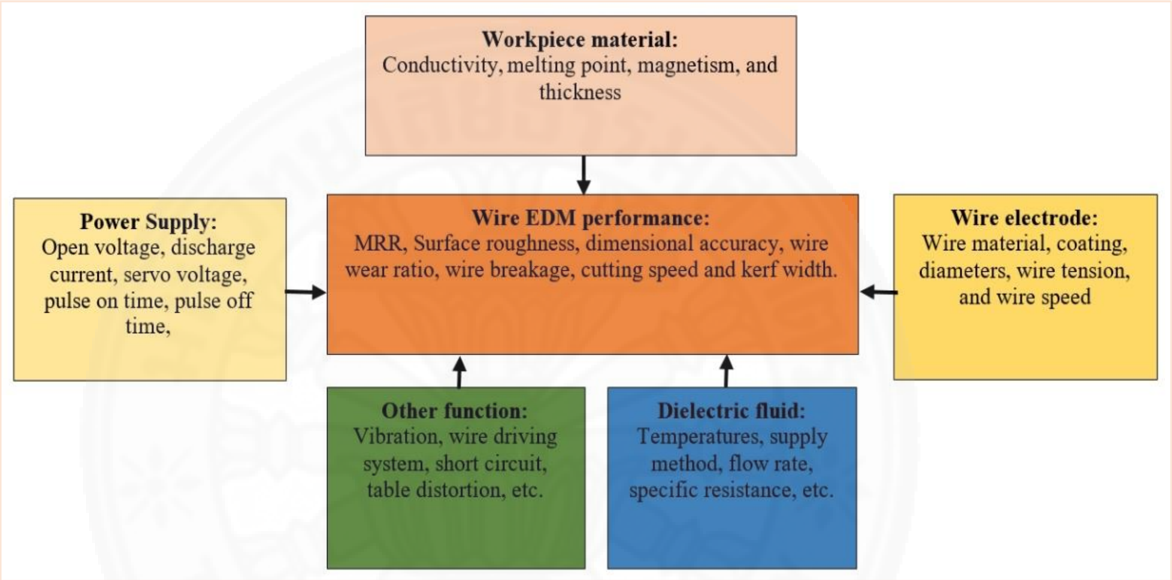


Figure 2.5 Wire-EDM parameters and performances (Mandal and Dixit, 2014)

2.5. 1 Wire-EDMing parameters

There are several parameters determine the performance of the wire-EDM operation as discussed below:

(1) Pulse on or pulse durtion

It was also called pulse duration which determines the duration of spark generated during wire-EDMing operation. The longer the duration, the more material removed in a certain time. Accordingly, the craters might be wider and deeper, hence the cut surface might be rougher. By means, by using the shorter duration of sparks lead to better (Huang, et al., 1999).

(2) Pulse off or pulse interval

If pulse on was the sparking duration, therefore, the rest time or interval time between one to another duration called pulse off. It also refers to time for the dielectric to being re-ionized which also affect the cutting rate of wire-EDMing operation. It means, increasing the pulse off time will lead to the increase of machining time. However, the greater the pulse off time the more stable sparking process achieved. Moreover, an insufficient of pulse off time may affect the retraction and cycle of the acceleration of the servo, so that make the operation cycle slower. Too short pulse off time also increases the usage of wire and the roughness of cut surface (Singh and Gerg, 2009).

(3) Discharge current

Discharge current also another essential element in wire-EDMing operation. Increasing the discharge current leads to the higher value of MRR and surface roughness, contrarily, it decreases wire wear ratio. Decreasing the wire wear ratio mean the ineffective wire-EDM operation due to the higher expense need to be paid. Therefore, properly select the discharge current value is very important and determine the effectivity of power usage (Singh and Gerg, 2009).

(4) Servo voltage (SV)

SV parameter functions to manage the position of the wire. In the process of wire-EDMing, the servo voltage will be varied based on the required gap of the workpiece and the electrode (Antar, et al., 2011). SV is also to advances and retracts of the wire postion. When the voltage getting higher than the set value, the wire advances, and if it is lower, the wire retracts. Therefore, in higher SV, the higher the gap between the wire and the workpiece. Higher SV also mean the lower amount of sparks, means cutting time increase and smoother cut surface gain. Moreover, a smaller value of SV lead to the more stable wire-EDMing and reducing the possibility of wire breakage (Aspinwall, et al., 2008).

(5) Open voltage

It determines the amount of voltage supplied in the wire-EDMing operation. The higher open voltage, the greater the discharge energy. However; this factor is the dependent factor. It implies, as the open voltage increase, the peak current will also increases for several number. In some Wire-EDM device, both factors show the machine voltage (Abulais, 2014).

(6) Wire feed

Wire feed means the rotating speed of the spool of wire to continuously fed into the sparking process. Wire feed determines effect the stability of the sparking process which may reduce the possibility of wire breakage. Also, higher wire feed may give better material removal rate (Singh and Gerg, 2009). When wire speed is increased, the wire consumption is also increasing and resulting in higher machining cost, whereas slow speed of wire may contribute to wire breakage.

(7) **Wire tension**

Wire tension is the device of wire-EDMing functions to keep the wire in constant tension while moving toward the workpiece. The value of wire tension is normally based on the thickness of the workpiece, the thicker of material the higher tension is required. Improperly adjust this value will contribute to the machining inaccuracies and breakage (Stephenson, 2007).

2.5. 2 Wire-EDM performance output

There are various variables to indicate the performance of wire-EDMing operation, as discussed below:

(1) Material Removal Rate or MRR

MRR is the total amount of the eroded material in in each second. Normally, it will be presented in term of volumetric MRR (mm^3/s) or weight MRR (mg/s). The MRR value depends on the material being cut, the thickness of material or even the properties of wire electrode used. Machining parameters also can determine the value of MRR, namely, pulse on/off time, servo voltage and wire feed. Moreover, the dielectric fluid condition such as temperature and resistance may affect the MRR (Stephenson, 2007).

(2) Surface Roughness (SR)

SR refers to the degree of surface smoothness of the cut sample resulted. There were various method to present Surface roughness based on the typical unit used such as Root mean Square (RMS) or Roughness average (Ra). Also, it is measured in either µm or µin (1 µm = 40 µin.) (Stephenson, 2007).

(3) Kerf Width

Kerf width is the amount of the wasting material during the wire-EDMing process. It can determine the machining accuracy of finish product and the internal corner radius of the product. Normally, kerf width equals to the wire diameter with servo voltage (Abulais, 2014).

(4) Wire Wear Ratio (WWR)

It presented the wire expense and length of cut ratio. It provides the degree of the machining efficiency, the higher the WWR, the more machining cost to be paid.

2.6 Wire-EDM performance optimization

Neraj et al. (2012) investigated the wire-EDMing parameters on high-strength low alloy steel (HSLA) using Response surface methodology, it revealed that cutting speed and dimensional deviation increases when the pulse on time increases. In order to investigate the influent of different wire-EDMing parameters on surface craters, Tosun et al. (2003) conducted an experiment using Taguchi's design method, the experiment indicated that an increase of pulse on time may increase the crater diameter and crater depth while increasing dielectric pressure reduce its. Thomas et al. (2015) identified the process parameter of sprint-cut wire EDM machine on EN31 steel using response surface methodology, it indicated that pulse on time and pulse off time has a great effect on MRR, in higher pulse on time resulted in the higher MRR, while the higher pulse off time reduce the MRR. In addition, Gautier et al. (2015) also studied the effect of wire-EDMing process parameter on titanium alloy using ANOVA and regression model, it revealed that the optimum surface roughness was found at the lower pulse on time and wire tension.

In order to achieve the higher cutting rate while reducing the kerf width of wire-EDMing process on titanium carbide reinforce manganese steel, Saha et al. (2013) utilized Hybridization of a radial basis function network (RBFN) and non-dominated sorting genetic algorithm (SNGA-II). The study indicated that the significant contribution of servo voltage on the kerf width and cutting speed. Increasing gap voltage results in increasing kerf width and decreasing cutting speed. Abdulkareem, et al. (2011) also found that the increase in gap voltage results in decreasing the surface cut quality. In order to identify the contribution of wire feed on the surface roughness, Shinde, et al. (2014) utilized the Taguchi approach, and they found that wire feed can increase the surface roughness, the faster wire feeding, the better surface quality obtained. Moreover, Islam, et al. (2010) revealed that wire tension has a big contribution on the dimensional accuracy. Characteristic of the linear error and flatness error and perpendicular error were influenced by the tension of the wire. More strength the wire caused the wire to be more stable and higher accuracy might be obtained.

Therefore, in order to achieve the optimum wire-EDM performance, several investigations had been carried out, also various methods had been proposed to get higher wire-EDMing performance through the investigation of machining parameters behavior during the cutting process (see Figure 2.6). According to Petel, et al. (2015), traditional approaches including the design of the experiment and mathematical model. Relating to design of experiment, Taguchi's method was the most popular method to deal with the wire-EDMing optimization process, following by factorial design and response surface methodology (RSM). While, for the mathematical model, several methods can be utilized such as Dynamic programming, Non-Linear programming, and Linear programming. For the unconventional approach, meta-heuristic search and a problem-specific heuristic search can be the option. For meta-heuristic search, Genetic algorithms (GA), Simulated annealing (SA), fuzzy optimization, neural network based method and ant colony optimization can be the solution method to deal with the stochastic variability in wire-EDM operation.

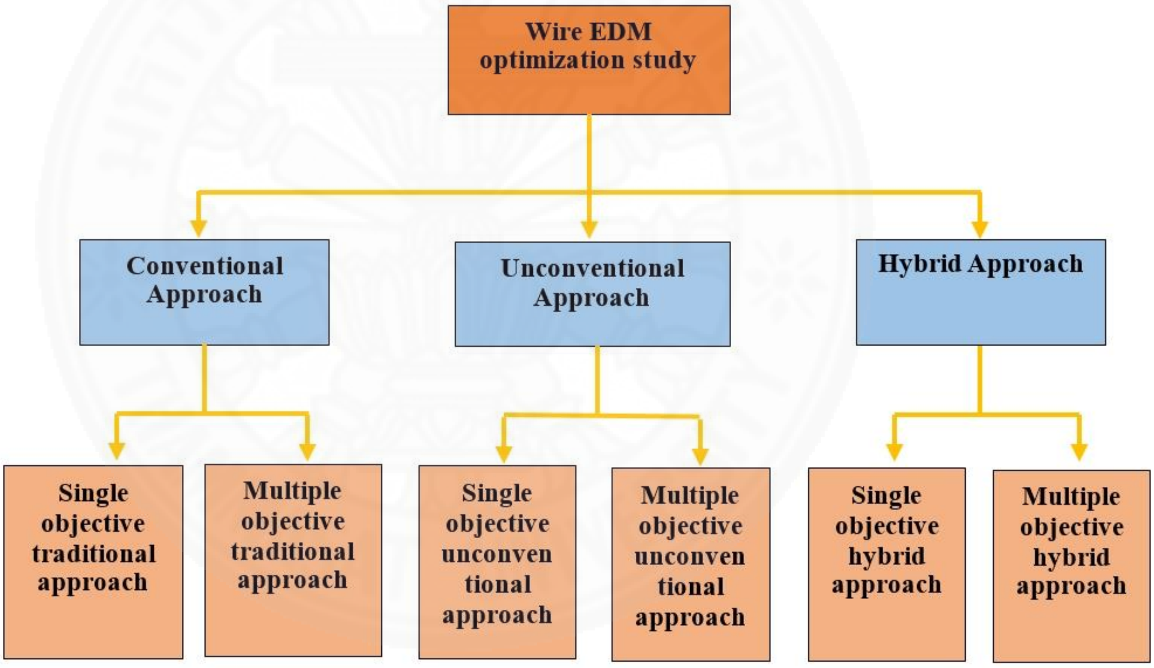


Figure 2.6 Types of optimization technique used in wire-EDM study (Chockalingam, et al., 2016)

Rao and Kalyankar (2014) reviewed the study during 2006 – 2012 in relation to optimization techniques adopted on the advanced machining study. They found that, regarding to wire-EDMing optimization process, the majority of the optimization were based on the Taguchi method and response surface methodology. Some works also attempted to adopt GA (Genetic Algorithm), ANN (Artificial Neural Network), and their modified version. In additions, the use of advanced optimization techniques such as BBO (Biogiography Based Optimization) and TLBO (Teaching Learning Based Optimization) was only a few research work. Table 2.1 specified various optimization techniques used recently in the case of the multiple objectives optimization study of wire-EDM.

Table 2.1 Recent techniques for multiple objective problem of wire-EDM study

Approach	**Author**	**Machining parameters**	**Responses**	**Techniques adopted**
Conventional approach	Mandal et al. (2015)	Pulse on time, pulse off time, dielectric flowrate, servo voltage	Spark gap, cutting speed surface roughness, wire wear ratio	Response surface methodology
	Singh, et al. (2015)	Pulse on time, pulse off time, wire tension, wire feed	Surface roughness, Material removal rate	Taguchi and analysis of regression
	Rao, et al. (2014)	Power input and Material Thickness	Material removal rate, and surface roughness	Non-linier programming

Conventional approach	Bobbili et al. (2015)	Servo voltage pulse on time ,pulse off time	Material Removal rate and surface roughness	Buckingham pi theorem
	Rao and Krishna (2014)	Particle Size, Pulse on time, Pulse off time and Wire tension	Surface roughness, wire wear ratio, Material removal rate	NSGA-II
Hybrid Approach	Shayan, et al. (2013)	Pulse on time, Pulse off time, Servo voltage, and Wire tension	Oversize and surface roughness	Back propagation neural network with Particle swarm optimization
	Fard, et al. (2013)	Pulse on time, Pulse off time, Servo voltage, Wire feed and Wire tension	Cutting speed, Surface roughness	ANFIS-ABC

2. 7 Wire-EDM assisting technique

In order to improve the usage of the wire-EDM and to adequately create the precise form of the cylinder on a certain hard-to-machine material. The underwater rotary spindle was designed and added by Qu et al. (2001) into a conventional two-axis wire-EDM to enable the process of creating a free forms cylindrical geometries. The experiment revealed that the present of an additional tool can increase the MRR of the wire-EDM process. Also, an experimental design using Taguchi’s approach also has been carried out by Haddad et al. (2009) on the wire electrical discharge turning machine on AISI D3 tool steel, the validity of the study confirmed that the machining performance of the machine increased significantly. Moreover, Guo et al. (1997) combined the technology of ultrasonic and wire-EDM in the machining of high chromium alloy steel. The study aimed to increase the machining performance of the wire-EDM technology. They found that the installation of ultrasonic vibration can increase the cutting efficiency of wire-EDM by 30% while reducing the roughness of the surface finish. Mohammadi et al. (2014) also investigated the effect of ultrasonic vibration of wire electrical discharge turning machine on the material removal rate and surface roughness in making the cylindrical geometric tool. The experiment was carried out by evaluating the factors namely, power, pulse off time, spindle rotation speed, and ultrasonic vibration over material removal rate. The results confirmed that the installation of the spindle device and ultrasonic vibration can significantly increase the MRR and reduced the surface roughness.

2. 8 Identified gaps in the literature

After reviewing related scientific study on the wire-EDM, several gaps have been identified such as:

(1) The researches that have been carried out mostly are wire-EDMing parameters investigation, performance optimization and prediction with several responses of interest namely, surface roughness, accuracy, cutting speed, kerf width, MRR and wire wear ratio. But very limited study take the machining cost as the part of the response.

(2) The study of wire-EDM have been conducted for several materials with single layer cutting process, the investigation of multilayer cutting process effect on the responses has not been fully explored.

(3) The investigation on the wire-EDM mostly conducted on the simple shape cut, very limited work investigates the effect of cutting parameters on the intricate shape cut material.

(4) Multiple responses optimization of the wire-EDM process by using hybrid technique has been given less attention in past study.

Chapter 3
Methodology

This chapter presented the design of experiment and method of analysis of the thesis in order to investigate the wire-EDMing performance. It consisted of the machine and material used, machining parameter and response of interest, performance evaluation, analysis method and multiple objective optimization.

3. 1 Wire-EDM machine

All experiments have been conducted in the faculty of manufacturing system and mechanical engineering laboratory, SIIT, Thammasat University by using Aristech Taiwan CNC Wire-EDM machine type CW10 (Figure 3.1)

Figure 3.1 Wire-EDM machine

The machine has been equipped with the moving coordinate worktable (Figure 3.2), AWT wire transport (Figure 3.3), filtration (Figure 3.4), and computerized panel control system (Figure 3.5). The machine used brass wire to perform the wire-EDMing operation stored in wire spooler of 5 kg, diameter of 0.25 mm, and tensile strength of 980 N/mm2. To guide and control the wire transport, the machine was equipped with the AWT (Automatic Wire Threading) wire transport system. Guide pulleys are mounted on the AWT system and can transport the wire up to 11 m/s. The workpiece therefore is placed on a moving coordinately worktable assisted by clamping system. A controlling system send a certain signal to the servo, then it rotates the gears system, extend to the screw and nuts, and finally the actions are converted into XY coordinate motion of the worktable to perform the operation.

Figure 3.2 Moving coordinate worktable

The motion of the worktable was according to the numerical code (NC Code) which is the input required in wire-EDM, it was consisted of the motion coordinate based on the required shape and also the machining code confirming the machining condition. All these function are generated on the MasterCam software. Moreover, control system, power supply system and electric relay was the component of the wire-EDM that are designed in a single unit called power cabinet as shown in figure 3.5.

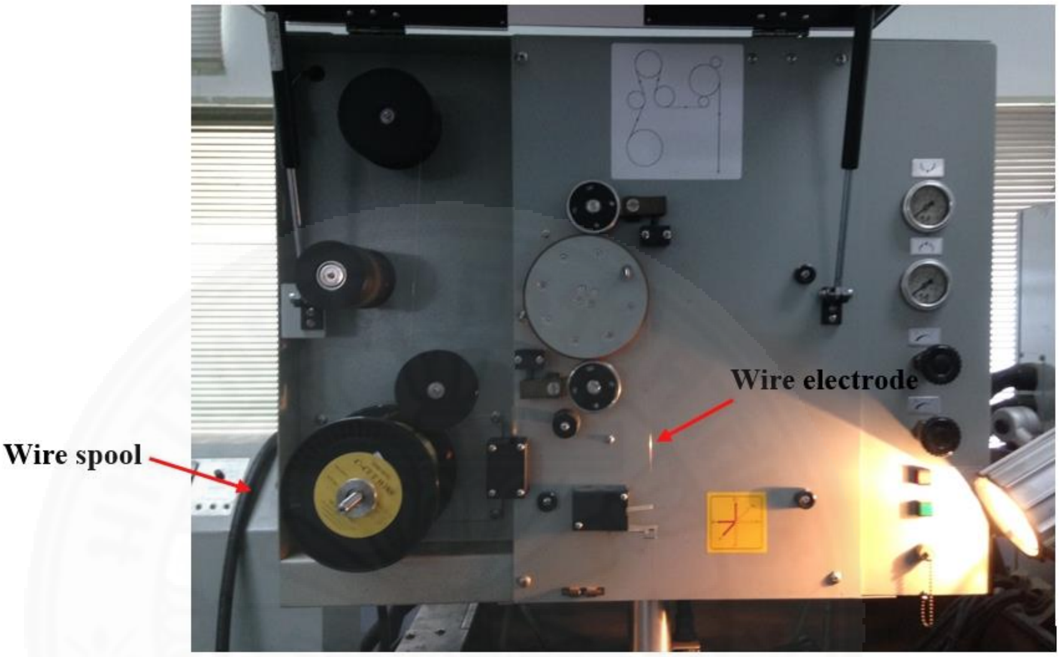


Figure 3.3 Wire-EDM AWT wire transport system

A mixture of distilled water and wire-EDM concentrate ion exchange resin were used as the dielectric fluid during the experimentation (Figure 3.6). In order to maintain the dielectric resistance, the machine was equipped with the circulated pump, temperature device, and conductivity meter (Figure 3.7). This system was functioned to maintain the temperature of the dielectric, controlling the dielectric conductivity, and filter the dielectric from the material powder as the result of the eroding process. In order to give a better insulation, the filtration system was also equipped with filtered resin pump. Finally, the temperature of dielectric fluid was maintained at 25 ^{0}C with the fan cooler machine.

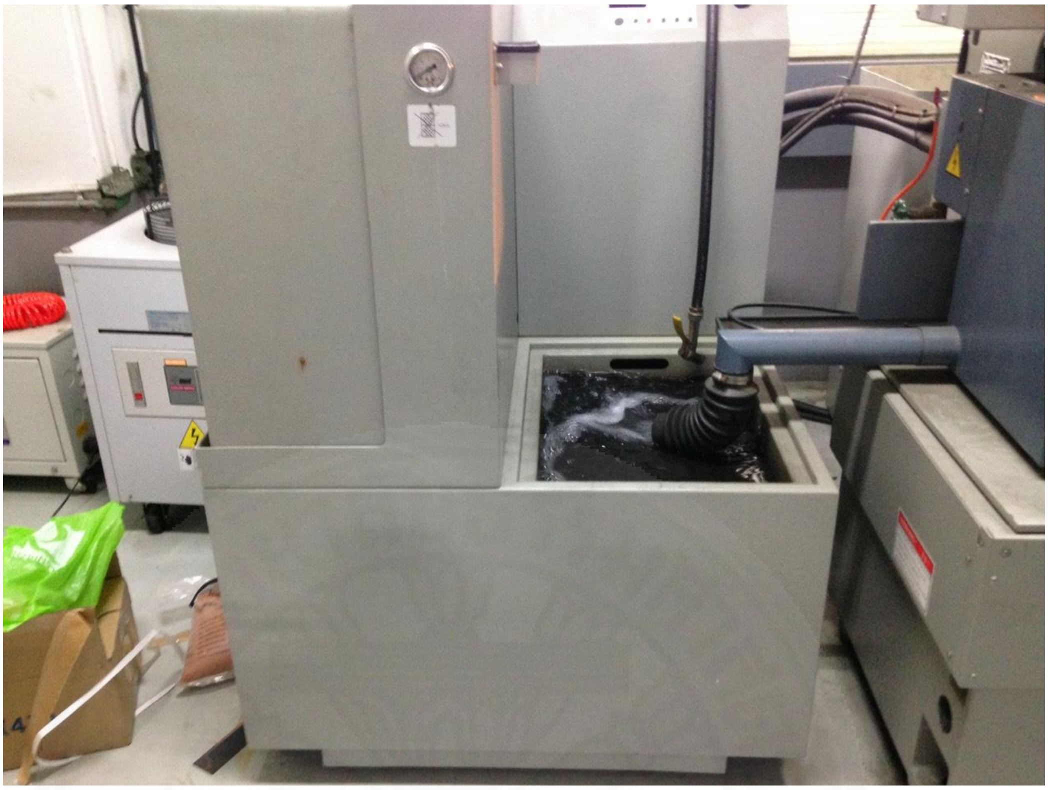


Figure 3.4 Wire-EDM dielectric filtration system

Figure 3.5 Panel and power cabinet

3. 2 Materials

SUS304 steel material with 12.7 mm of thickness used as the workpiece (Table 3.1). SUS304 steel is an austenitic stainless steel which sometimes referred to as 18-8 stainless as it has a nominal composition of 18% Chromium and 8% Nickel. It was broadly utilized almost in every industrial application. Due to the unique characteristic of it, such as mechanical strength, architecture, weldability, corrosion resistance and chemical properties, thus make it becoming the most preferable steel grade. SUS304 steel grade material also used in various application such as: pharmaceutical industry, food industry, and paper industry.

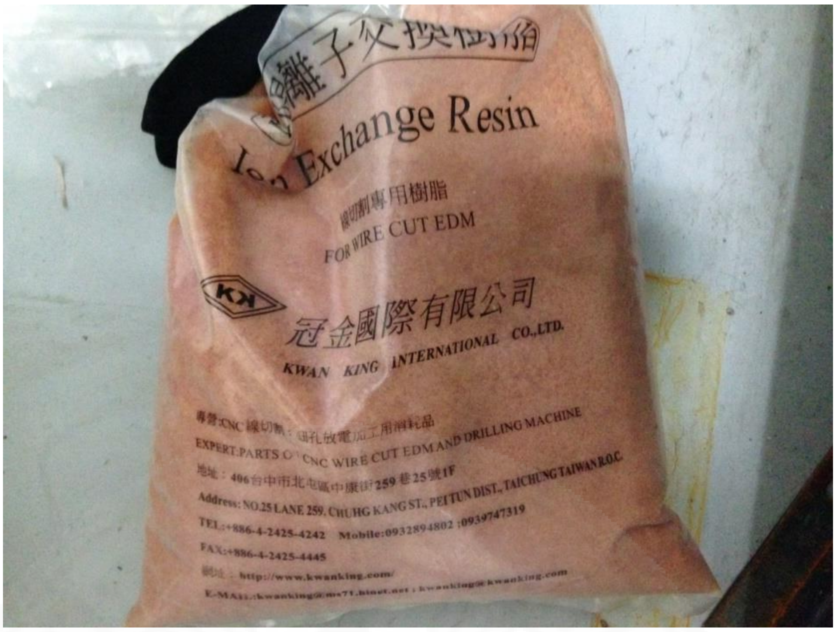


Figure 3.6 Ion exchange resin for wire-EDM dielectric

Figure 3.7 (A) Resin pump, (B) Dielectric conductivity meter and (C) Temperature controlling device

The material for the experiment were constructed in both single layer and double layer, in order to investigate the multiple layer strategy effect on the machining performance.

Table 3.1 The composition of SUS304 steel grade

Element	Carbon (C)	Chromium (Cr)	Manganese (Mn)	Nickel (Ni)	Phosphorous (P)	Sulphur (S)	Silicon (Si)	Ferrous (Fe)
Content (%)	0.08	18.5	1.9	8.4	0.026	0.016	0.4	Balance

3. 3 Experimentation

3.3. 1 Samples preparation

The workpieces are in forms of square rod of 300 mm × 50 mm × 12.5 mm size mounted on the wire-EDM worktable machine. The machine tool therefore was assigned to cut into square shape 10 mm × 10 mm and gear shape. The close up view of the rod being mounted on the worktable of the machine was shown in Figure 3.8. Moreover, the entire samples for the present study were provided in Figure 3.9.

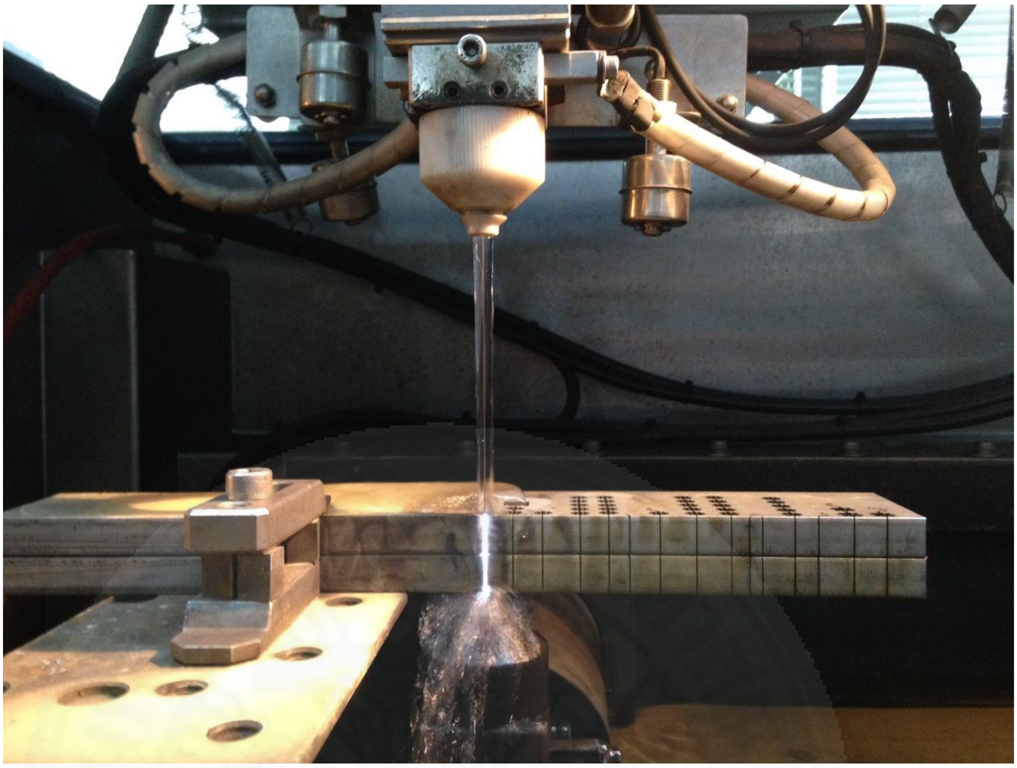


Figure 3.8 Workpiece and the sparking process on wire-EDM worktable

3.3. 2 Procedure

There were several steps conducted in the experiment, such as:

1. The samples material were cleaned up before clamping on the worktable.
2. The workpieces were mounted horizontally (in WCS axis) on the worktable.
3. The similar NC code input was used for the entire cutting condition.
4. The line space (3 mm) is provided in each design to give time for parameters adjustment

Also, several actions are taken to avoid the environmental effect on the response:

1. The temperature of the dielectric maintain at 25 ^oC.
2. The dielectric resistance was set at 45 A and the gauge was maintain at 2 kg/cm^2.

3. While conducting the experiment, the wire-EDM room is adjusted at 23 ^{o}C (air condition temperature).
4. After finishing each experiment condition, the samples were cleaned up by using mineral water and dried before measuring the cut surface.

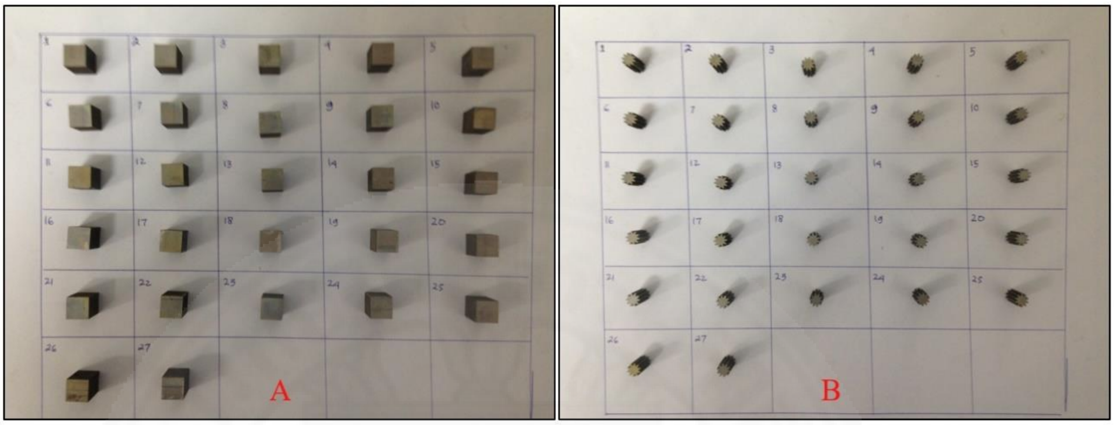


Figure 3.9 Samples: (A) Square part case and (B) Gear part case

3.3. 3 Pilot Experiment

This pilot experiments aim to study the influent of the selected machining factors on the machining output namely machining cost, MRR, Surface roughness, and machining Deviation. There are five parameters have been selected and varied during the experiment that are Servo voltage (SV), pulse on time (Ton), Pulse off time (Toff), wire feed (WF), and Wire tension (WT). The parameter selection was based on the literature review and preliminary study. Taguchi's design L_{27} with five factors and three levels of each factors is proposed to be used as the experimental design. The parameters and the levels of selected parameters is listed in Table 3.2. The experimental design of Taguchi's L_{27} was created through MINITAB17 software (Table 3.3).

Table 3.2 List of factors and levels

Factors	Symbol	Level 1 (Actual)	Level 2 (Actual)	Level 3 (Actual)
Servo Voltage (SV) (volt)	A	45	50	55
Pulse On (Ton) (μs)	B	4	5	6
Pulse Off (Toff) (μs)	C	15	20	25
Wire Feed (WF) (mm/s)	D	4 (60)	6 (110)	8 (170)
Wire Tension (WT) (g)	E	8 (1000)	10 (1390)	12 (1840)
Open Voltage (OV) (volt)		80	80	80
ARC On time (AN)		1	1	1
ARC Off time (AFF)		25	25	25
Feed rate override (FR)		1	1	1
Feed rate (F)		10	10	10
Water flow (WL) (kg/cm^2)		1.5	1.5	1.5
Feed rate mode (FM)		0	0	0

Table 3.3 Taguchi's L_{27} orthogonal array

Exp. No	**A**	**B**	**C**	**D**	**E**
1	1	1	1	1	1
2	1	1	1	1	2
3	1	1	1	1	3
4	1	2	2	2	1
5	1	2	2	2	2
6	1	2	2	2	3
7	1	3	3	3	1
8	1	3	3	3	2
9	1	3	3	3	3
10	2	1	2	3	1

11	2	1	2	3	2
12	2	1	2	3	3
13	2	2	3	1	1
14	2	2	3	1	2
15	2	2	3	1	3
16	2	3	1	2	1
17	2	3	1	2	2
18	2	3	1	2	3
19	3	1	3	2	1
20	3	1	3	2	2
21	3	1	3	2	3
22	3	2	1	3	1
23	3	2	1	3	2
24	3	2	1	3	3
25	3	3	2	1	1
26	3	3	2	1	2
27	3	3	2	1	3

3.3. 4 Preliminary Study

The preliminary study has been conducted aimed to get the possible machining setup option to conduct the experiment. Taking into consideration for this purpose are the wire-breakage and the wire speed (higher is better). The initial setup parameters are obtained from the machine book of guideline, then, adjusted until it reach the maximum speed without any wire-breakage. In order to conduct this processes, a case study of knife making are proposed. Including the line contour, corner contour and various angle contour to see the performance of wire-EDM tool on difference contour conditions.

Also, the grade and thickness of the steel material are also varied in this preliminary works to see the feasibility and its contribution to wire-EDM performance. According to Hajad and Rianmora (2016), the properties of the steel and thickness of the material affect greatly on the performance of wire-EDM. Also, the contour path angle give the significant contribution to the wire-EDM performance especially for the cutting speed. Table 3. 10 shows the preliminary work results.

Table 3. 4 Preliminary work results: Knife making case study

Thickness \ Length	90 mm	100 mm	110 mm
1.5 mm	 10° tip angle	 15° tip angle	 20° tip angle
2 mm	 10° tip angle	 15° tip angle	 20° tip angle
3 mm	 15° tip angle	 20° tip angle	 10° tip angle

3. 4 Machining performance Analysis

3. 4. 1 Machining Cost (MC)

In the present work, instead of calculating the machining expense by using the wire wear ratio, the machining cost in the present work is calculated through the following function. The machining cost for each experimental run have been quantified according to the expense of wire and electrification cost (Eq. 1).

$$MCi = \big((WFi \times Cw) + (Pi \times Cp\big) \times ti \quad (1)$$

And to calculate the usage of electrical power, by using Eq. 2.

$$Pi = \mathrm{Vi} \times \mathrm{IPi} \quad (2)$$

Where:

MC_i is the Machining cost (USD)

WF_i is the Wire Feed (mm/s),

C_w is the cost of wire (USD/mm),

P_i is the usage of electrical power (watt/hr),

V_i is the Servo (volt)

IP is the mean of peak current (A)

C_p is the cost of electrical power (USD/Kwh),

t_i is the operational time.

3. 4. 2 Material Removal Rate (MRR)

The MRR was calculated as volumetric MRR (mm^3/s) by using Eq. 3. The cutting speed (Cs) was calculated directly through length of cut divided by cutting time. Kerf width in this experiment was measured through a graphical analysis as shown in Figure 3.10. While, the material thickness is remain constant for the entire experiment conditions.

$$MRR = Cs \times L \times b \tag{3}$$

Where, Cs is Cutting speed (mm/min), L is material thickness (mm) and b is kerf width.

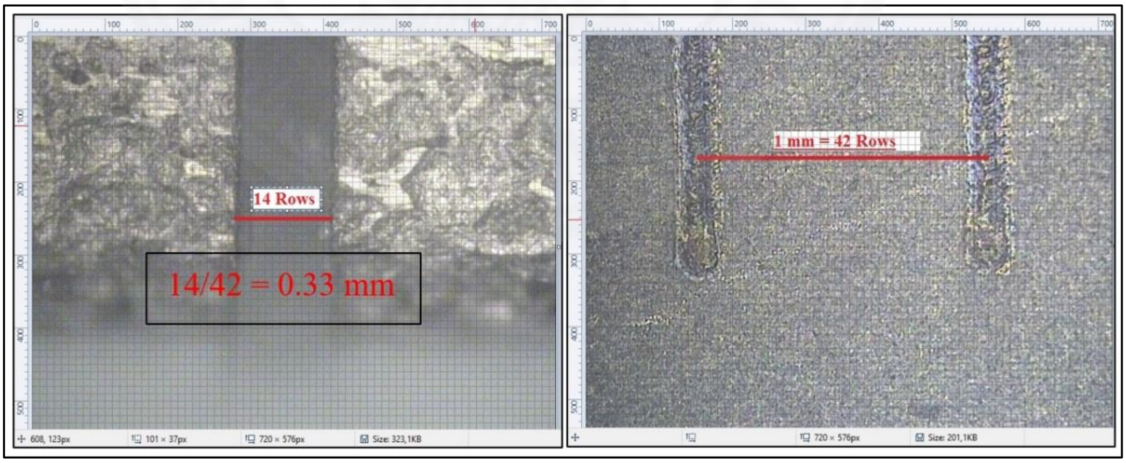


Figure 3.10 Graphical analysis for kerf width

3. 4. 3 Surface roughness (SR)

SR is a term for the surface texture of a material. It was measured as a vertical deviation of the surface of material from the ideal surface. The large deviation present a rough surface, however small deviation mean smooth surface. In the present work, the SR of the cut result was measured by using Mitotuyo Surftest sj301 as constructed in Figure 3.11.

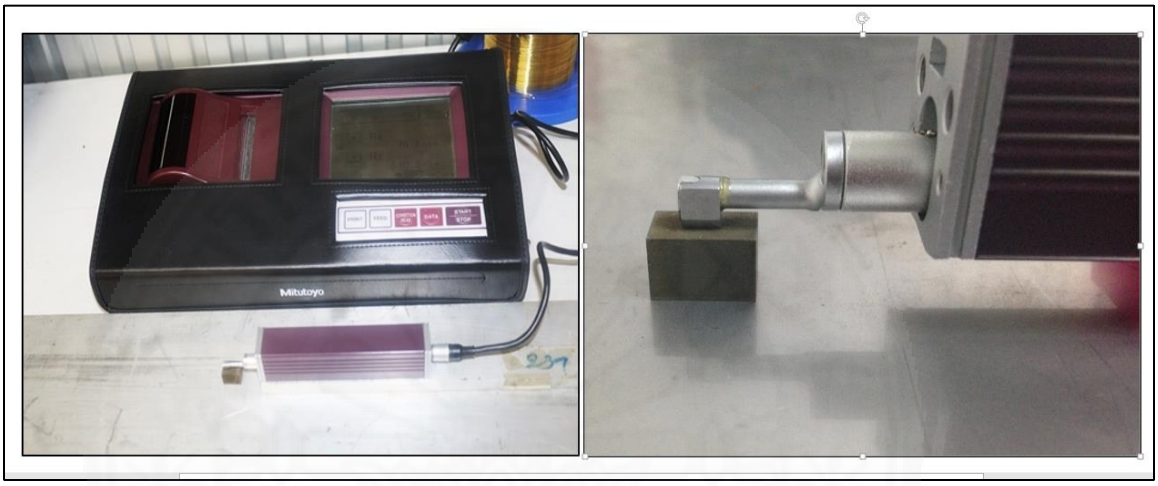


Figure 3.11 Surftest SJ310 for surface roughness measurement

3. 4. 4 Machining accuracy

The accuracy of the machining process was measured through calculating the dimensional deviation. The deviation therefore calculated as the percentage deviation as specified in Eq. 4.

$$Percentage\ of\ Deviation : \frac{expected\ size - actaul\ size}{expected\ size} \times 100\% \qquad (4)$$

Also, the surface integrity of the cut surface has been analyzed through micrograph analysis device (Figure 3.12) to give the better visualization of the machining parameters effect on the cut quality.

Figure 3.12 Microscope scanning device with 10x, 20x, 50x and 100x magnification.

3. 5 Method of analysis

3. 5. 1 Signal-to-noise ratio

In the present work, Taguchi's method was utilized to analyze the effect of the selected parameters on the response of interest. According to Taguchi's method, there were two category of the factor: (1) controllable factor and (2) uncontrollable factor. Controllable factor are factors could be adjusted easily. However, uncontrollable factor are normally associated to the environmental condition such as temperature. The optimal setup parameters are determined through the optimum machining performance. According to the Taguchi' method (Montgomery, 1992), there were three possible types of the response characteristics. That is the higher is better (HB), smaller is better (SB) and nominal is better (NB). According to these characteristics, therefore MRR was set to be HB response, while others response (Machining Cost, Surface roughness, and deviation) are set to be SB response.

$$ {}^{S}/_{N} \ for \ \text{HB} = -10 \log 10 \ \int_{i=1}^{n} \frac{\left(\frac{1}{yi^2}\right)}{n} \quad (5) $$

$$ {}^{S}/_{N} \ for \ LB = -10 \log 10 \int_{i=1}^{n} \frac{yi^2}{n} \quad (6) $$

Where, n is the replication of treatment, yi is the mean response

3. 5. 2 Analysis of variance (ANOVA)

ANOVA was a popular statistical method to specify the percentage of contribution of every single factor on the individual response. To do it, several calculations are required such as Degree of freedom (DF), sum of square (SS), mean square error (MSE), F-test, P-value and percentage of contribution (Montgomery, 1992).

The degree of freedom (DF) is calculated by using Eq. 7.

$$ Df = n - 1 \quad (7) $$

Where n is the number of level.

Sum of Square (SS) is to quantify of deviation of the experimental data from mean value of the data.

$$ \text{SS} = \sum_{i=1}^{N} (yi - Ta)^2 \quad (8) $$

Where N= number of response observation, Ta is the average of all observation and yi is value of the i^{th} response.

Error sum square (SSE) is squared deviation of observations from factor (A) averages

$$SSE = \sum_{j=1}^{kA} \sum_{i=1}^{nAi} \left(yi - A_j\right)^2 \quad (9)$$

Mean square (MS) is the value of sum square divided by the degree of freedom (Df).

$$MS = {}^{SS}/_{Df} \quad (10)$$

Error mean square (MSE) is the value of error sum square divided by the degree of freedom.

$$MSE = {}^{SSE}/_{Df} \quad (11)$$

F-Value is the value of mean square divided by error mean square.

$$F - value = {}^{MS}/_{MSE} \quad (12)$$

3. 6 Multiple objective optimization by using utility concept

Costumers would be willing to buy a product through several characteristics. These, different characteristics therefore evaluated using the composite index. The index shows the importance of the expected product. Thus, if x_{ij} was the utility value of a product on the characteristic j and there are n characteristics that need to be evaluated, then the overall utility equation could be expressed as follow (Goswani and Kumar, 2014):

$$U\ (\ x1, x2, \ldots xn) = f\ [\ U1(x1), U2\ (x2), \ldots Un(xn)] \quad (13)$$

Then in linier case, it can be expressed:

$$U\ (x1, x2, .. xn) = \sum_{j=1}^{n} Wj\ U(xij) \quad (14)$$

Where, W_j is the weighted for the characteristic j then the total of the weighted value for all characteristics are equal to 1. If these utility were expected to be maximized, then the quality characteristics which are considered to be evaluated will be automatically optimized.

At first, the expected scale of each single characteristic was calculated to find the preference number for each characteristic and later this value is weighted to get the overall utility. The expected scale must be an algorithm. The minimum quality value for each characteristic was set to be 0 while the best quality was set to be 9. Then, if the log scale is chosen, the preference number (Pij) can be given by Eq. 15.

$$Pij = A \log\left(\frac{xij}{Xij}\right) \tag{15}$$

Where, x_{ij} is any value of quality characteristic in this case, the value is from the SN ratio, and X_{ij} is the minimum value of the certain quality characteristic and it was constant in nature. In the optimum value (xij*) of characteristic j, Pij = 9, so Pij can be expressed by Eq. 16.

$$Pij = A \log(\frac{x_{ij}^{*}}{X_{ij}}) \tag{16}$$

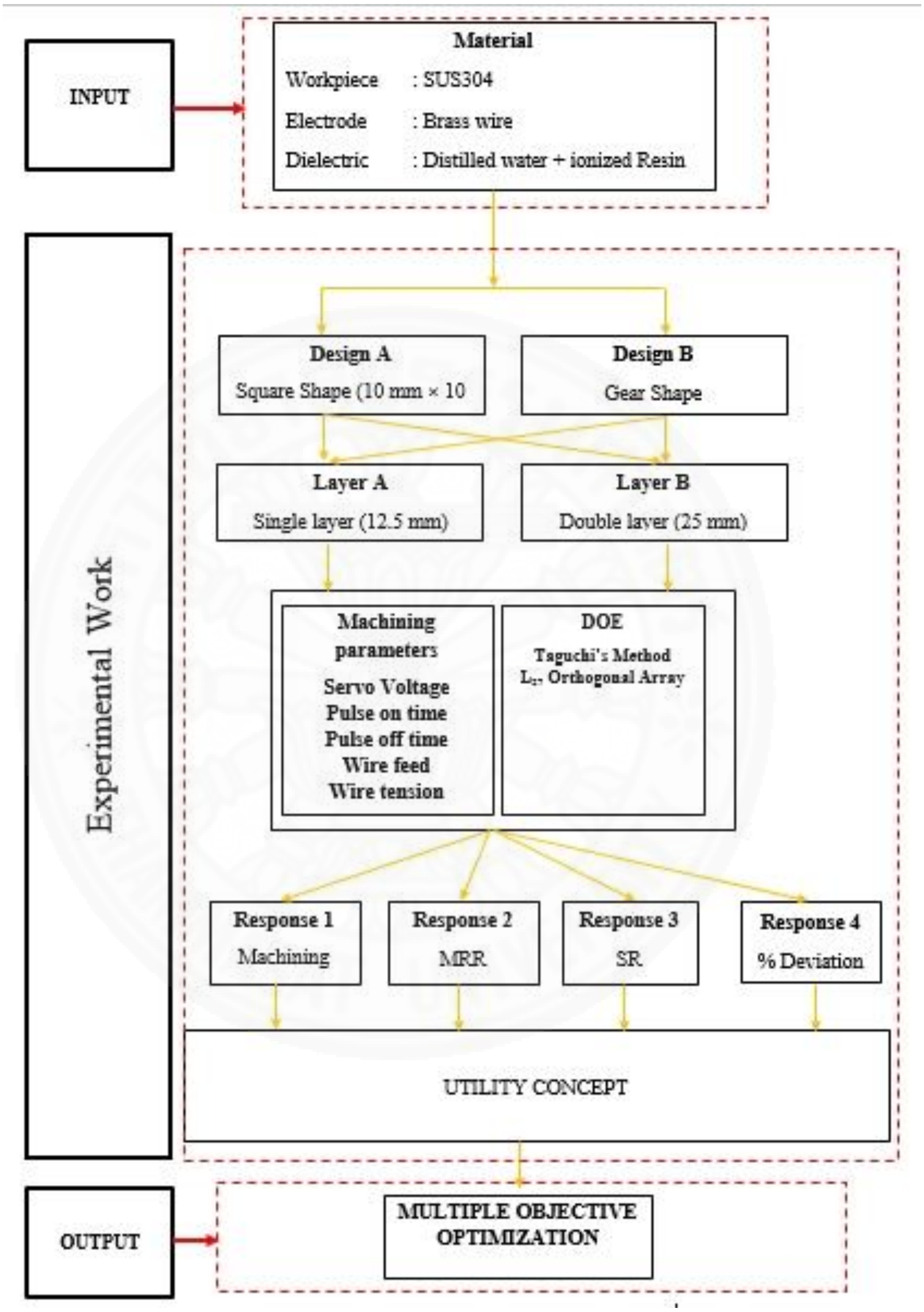
The value of A can be determined by using equation 16, therefore the A value can be used to calculate the P value for all characteristics in all i_{th} trial. And the next step is to assign the weight for the quality characteristics. This was based on the experimenter subjective. In this case the weight for all four responses will be equal to 0.25 (all responses have the same level of importance, therefore, the sum of all utility is equal to 1).

Therefore, the overall utility can be calculated using Eq. 17:

$$Uij = \sum_{j=1}^{p} Wj \times Pij \tag{17}$$

Where, j is the quality characteristic of the response.

3. 7 Experimental concept



Chapter 4
Results and Discussion

This chapter presented the details of the experimental work performed on Wire-EDM operations including the results and discussion. The objective of the present work was to investigate the process parameters of wire-EDMing on the output parameters e.g. machining cost, MRR, surface roughness, and accuracy by using two different strategies: single layer and multiple layer. Also, the effect of the machining parameters on the multi contour shape is being investigated. The plots of parameters effect on each single response have been generated using signal to noise ratio plot in MINITAB. Moreover, the ANOVA table of obtained results have been provided to show the contribution of the factors in every single output. After that, the signal noise to ratio also for each output has been drawn to see each the characteristic of the machining parameters. Then, multi objective optimal condition have been calculated for machining cost, MRR, surface roughness and accuracy.

4. 1 Square part with single layer case

4.1.1 Machining cost

The results for machining cost for the square shape and single layer condition are given in Table 4.1. In the present work, the overall machining cost of wire-EDM was dependent on wire electrode cost and electrical power cost, since both of them were the major cost in wire-EDM operation, excluding, dielectric fluid cost and other maintenance and service cost. Although, the service cost and maintenance cost are major in wire-EDM operation, however, these factor not affect the directly to the machining performances. Therefore, the quantification of the overall machining cost was based on Eq. 1. The unit cost of wire and unit cost of electrical power were estimated in the present work USD $9.5\times10^{-}6$/mm and USD 1.7×10^{-1}/unit KWh, respectively.

Table 4.1 Machining cost for square part with single layer case

No	Servo Voltage	Pulse On	Pulse Off	Wire Feed (mm/s)	Wire Tension (gr)	Wire Cost (USD)	Power Cost (USD)	Total Cost (USD)
1	45	4	15	60	1000	0.88	0.21	1.09
2	45	4	15	60	1240	0.87	0.22	1.09
3	45	4	15	60	1890	0.87	0.22	1.09
4	45	5	20	90	1000	1.20	0.20	1.40
5	45	5	20	90	1240	1.19	0.20	1.39
6	45	5	20	90	1890	1.19	0.21	1.39
7	45	6	25	110	1000	1.25	0.19	1.43
8	45	6	25	110	1240	1.24	0.19	1.43
9	45	6	25	110	1890	1.22	0.18	1.41
10	50	4	20	110	1000	1.86	0.27	2.13
11	50	4	20	110	1340	1.83	0.27	2.10
12	50	4	20	110	1890	1.83	0.27	2.10
13	50	5	25	60	1000	0.86	0.24	1.11
14	50	5	25	60	1240	0.86	0.24	1.10
15	50	5	25	60	1890	0.86	0.24	1.10
16	50	6	15	90	1000	0.93	0.20	1.13
17	50	6	15	90	1240	0.93	0.20	1.13
18	50	6	15	90	1890	0.93	0.20	1.12
19	55	4	25	90	1000	1.79	0.34	2.13
20	55	4	25	90	1240	1.76	0.34	2.09
21	55	4	25	90	1890	1.75	0.34	2.09
22	55	5	15	110	1000	1.34	0.24	1.58
23	55	5	15	110	1240	1.34	0.24	1.57
24	55	5	15	110	1890	1.33	0.24	1.56
25	55	6	20	60	1000	0.62	0.21	0.84
26	55	6	20	60	1240	0.62	0.21	0.84
27	55	6	20	60	1890	0.62	0.21	0.83

According to Figure 4.1, the machining cost for the condition of single layer cut and square shape sample, the machining cost was optimum at the lowest level of servo voltage, highest level of the pulse on factor, lowest level of pulse off factor, lowest level of wire feed factor, and highest level of wire tension factor. According to Table 4.2, the wire feed has given the highest contribution to the machining cost, followed by pulse on factor, pulse off factor, servo voltage, and wire tension factor, respectively. According to this experimental work, the wire expense has been the major cost of wire-EDM operation, to obtain the optimum machining cost, therefore wire feed need to be adjusted as low as possible. However, at the lower wire feed, the possibility of having wire breakage is increase.

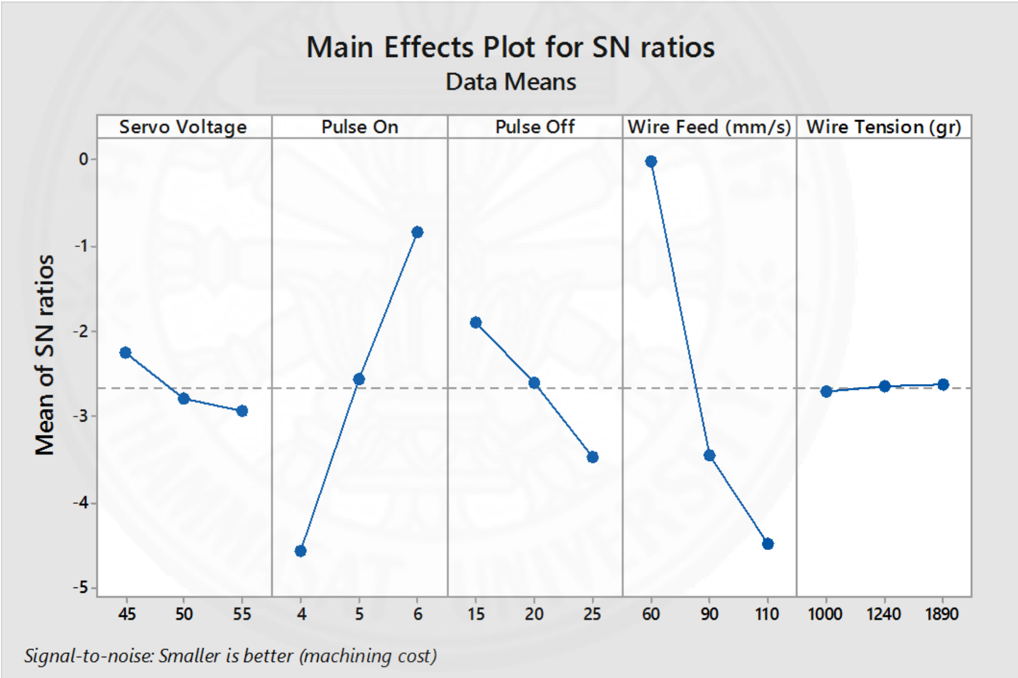


Figure 4.1 SN ratio for machining cost (condition: single layer, square shape)

The result of machining costs were also analyzed using ANOVA method in order to investigate the significance of each parameter on the performance measures. ANOVA result for the mean machining cost was (99% confidence interval) given in the Table 4.3. Therefore, the F-test was performed on the variance data for each factor to find the level of significance for every single factor. The larger the F-test for a certain parameter, the greater the influence of the mentioned parameter on the response because it in charge in that process. Table 4.3 showed the higher value of F-test was achieve from the wire feed factor (18272.6), followed by pulse on factor (14676.7), pulse off factor (2853.76), servo voltage factor (1480.75), and wire tension factor (8.76). According to the ANOVA table, wire tension factor was seem to be insignificance for the machining cost.

Table 4.2 Response table of machining cost for square part with single layer case

Level	Voltage	Pulse on	Pulse off	wire feed	wire tension
1	1.303	1.767	1.262	1.009	1.426
2	1.446	1.358	1.446	1.542	1.416
3	1.503	1.127	1.544	1.701	1.41
Delta	0.2	0.461	0.282	0.691	0.016
Rank	4	2	3	1	5

4.3 ANOVA table of machining cost for square part with single layer case

Source	DF	Adj SS	Adj MS	F -Value
Servo voltage	2	0.19113	0.09557	1480.75
Pulse on	2	1.89444	0.94722	14676.7
Pulse off	2	0.36836	0.18418	2853.76
wire feed	2	0.35859	0.1793	18272.6
Wire tension	2	0.00113	0.00057	8.76
Error	16	0.00103	0.00006	
total	26	4.81469		
Model Summary				
S	R-sq	R-sq (adj)	R-sq (pred)	
0.0080336	99.98%	99.97%	99.94%	

4.1.2 Material Removal Rate (MRR)

Table 4.4 presented the results of the MRR output at the condition of single layer and square shape sample. The effect plot of SN ratio (larger is better) for each single factors on the MRR values was given in Figure 4. 2. It indicated that MRR is increase when the pulse on time and wire tension increase, while decrease when the servo voltage and pulse of time increase. As the pulse on time increase, more sparks produced and the higher amount of material can be eroded in each second. However, in higher pulse off time, the discharge current will be decrease in each second, therefore it reduce the cutting speed and MRR. Also, an increase in servo voltage reduce the discharge current in the cutting process, therefore, it leads to lower MRR.

According to Table 4.5, the highest contribution to the MRR was given by pulse on time, followed by servo voltage, pulse off time, wire feed, and wire tension, respectively. The ANOVA for the mean MRR at 99% confidence interval was given in Table 4.6. It shows that the highest F-test was achieved from pulse on time factor (49129.1), followed by servo voltage (8107.51), pulse off time (4358.87), wire feed (168.58), and wire tension (22.78). In this experiment, the wire feed and wire tension factors seem to be insignificant on the MRR. According to the literature (Gerg, 2009), the wire feed is functionated to give the higher stability of the sparking process. A higher wire feed can result in the higher cutting rate and MRR due to the more wire fed to the sparking process which may lead to the higher discharge. However, according to results obtained, at wire feed (80 mm/s), the MRR reduced, and increases again at wire feed (110 mm/s). This may due to the environmental factors such as the temperature instability and dielectric conductivity degradation.

Table 4.4 MRR for square part with single layer case

Servo Voltage (volt)	Pulse On	Pulse Off	Wire Feed (mm/s)	Wire Tension (gr)	cutting speed (mm/min)	kerf width (mm)	MRR (mm^3/s)
45	4	15	60	1000	1.560	0.380	0.124
45	4	15	60	1240	1.569	0.380	0.124
45	4	15	60	1890	1.571	0.380	0.124
45	5	20	90	1000	1.716	0.389	0.139
45	5	20	90	1240	1.727	0.389	0.140
45	5	20	90	1890	1.732	0.389	0.140
45	6	25	110	1000	2.017	0.400	0.168
45	6	25	110	1240	2.025	0.400	0.169
45	6	25	110	1890	2.051	0.400	0.171
50	4	20	110	1000	1.349	0.346	0.097
50	4	20	110	1240	1.372	0.346	0.099
50	4	20	110	1890	1.375	0.345	0.099
50	5	25	60	1000	1.584	0.355	0.117
50	5	25	60	1240	1.589	0.355	0.117
50	5	25	60	1890	1.596	0.354	0.118
50	6	15	90	1000	2.212	0.367	0.169
50	6	15	90	1240	2.214	0.367	0.169
50	6	15	90	1890	2.220	0.366	0.169
55	4	25	90	1000	1.149	0.311	0.075
55	4	25	90	1240	1.170	0.311	0.076
55	4	25	90	1890	1.172	0.311	0.076
55	5	15	110	1000	1.871	0.323	0.126
55	5	15	110	1240	1.879	0.323	0.127
55	5	15	110	1890	1.893	0.323	0.127
55	6	20	60	1000	2.196	0.332	0.152
55	6	20	60	1240	2.204	0.332	0.153
55	6	20	60	1890	2.222	0.332	0.154

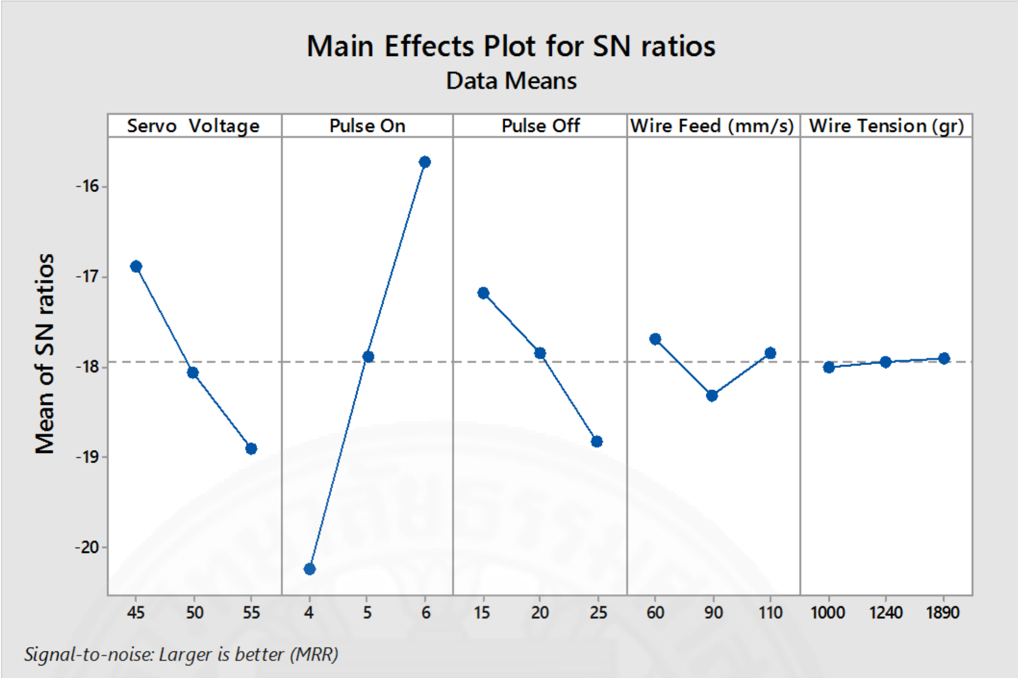


Figure 4.2 SN ratio for MRR (condition: single layer, square part)

Table 4.5 Response table of MRR for square part with single layer case

Level	Voltage	Pulse on	Pulse off	Wire feed	Wire tension
1	0.1443	0.09924	0.13993	0.13139	0.12958
2	0.1283	0.12793	0.13026	0.12811	0.13032
3	0.11828	0.16371	0.12069	0.13138	0.13097
Delta	0.02601	0.06447	0.01924	0.00328	0.00139
Rank	2	1	3	4	5

Table 4.6 ANOVA table of MRR for square part with single layer case

Source	DF	Adj SS	Adj MS	F -Value
Servo voltage	2	0.003099	0.00155	8107.51
Pulse on	2	0.01878	0.00939	49129.1
Pulse off	2	0.001666	0.000833	4358.87
wire feed	2	0.000064	0.000032	168.58

Wire tension	2	0.000009	0.000004	22.78
Error	16	0.000003	0	
total	26	0.023622		
Model Summary				
S	R-sq	R-sq (adj)	R-sq (pred)	
0.0004372	99.99%	99.98%	99.96%	

4.1.3 Surface Roughness (SR)

Table 4.4 shows the result for the MRR response at the condition of single layer and square shape sample. SN ratio plot for surface roughness are shown in figure 4.3 which shows the variation of surface roughness in deferent input parameters. It indicated that the optimum surface roughness can be achieved at the fist level servo voltage factor, the third level of pulse on factor, the third level of pulse off factor, the first level of wire feed factor, and the third level of wire tension factor. As the pulsating duration increases, the discharge current increases, and this increases the thermal energy to produce the larger crater. Thus, the surface roughness value increases in the workpiece. In higher servo voltage, the greater space in between the wire electrode and workpiece, also the lower amount of spark may be produced during the cutting process, this lead to the lower crater produce in the surface cut. Moreover, at higher speed of wire, the more cycling rate of wire feed can be achieve, this may lead to a lower sparking and lower crater gives in the surface. According to the response table of surface roughness (Table 4.8), the highest contribution to effect the roughness on the surface cut is gain from the pulse on time factor, followed by pulse off time, wire feed, wire tension, and servo voltage, respectively.

Table 4.7 SR for square part with single layer case

Servo Voltage	Pulse On	Pulse Off	Wire Feed (mm/s)	Wire Tension (gr)	SR (μm)
45	4	15	60	1000	2.16
45	4	15	60	1240	2.47
45	4	15	60	1890	2.27
45	5	20	90	1000	2.30
45	5	20	90	1240	2.32
45	5	20	90	1890	2.30
45	6	25	110	1000	2.36
45	6	25	110	1240	2.46
45	6	25	110	1890	2.42
50	4	20	110	1000	1.94
50	4	20	110	1240	1.98
50	4	20	110	1890	2.06
50	5	25	60	1000	2.13
50	5	25	60	1240	2.34
50	5	25	60	1890	2.27
50	6	15	90	1000	2.63
50	6	15	90	1240	2.74
50	6	15	90	1890	2.76
55	4	25	90	1000	1.92
55	4	25	90	1240	1.92
55	4	25	90	1890	1.94
55	5	15	110	1000	2.31
55	5	15	110	1240	2.32
55	5	15	110	1890	2.35
55	6	20	60	1000	2.45
55	6	20	60	1240	2.46
55	6	20	60	1890	2.65

The ANOVA with the mean surface roughness at 95% confidence interval is given in Table 4.9. According to Table 4.9, the highest f-test value was coming from pulse on time factor (112.08), followed by pulse off factor (32.57), wire feed factor (6.06), wire tension factor (5.27), and servo voltage factor (3.79), respectively.

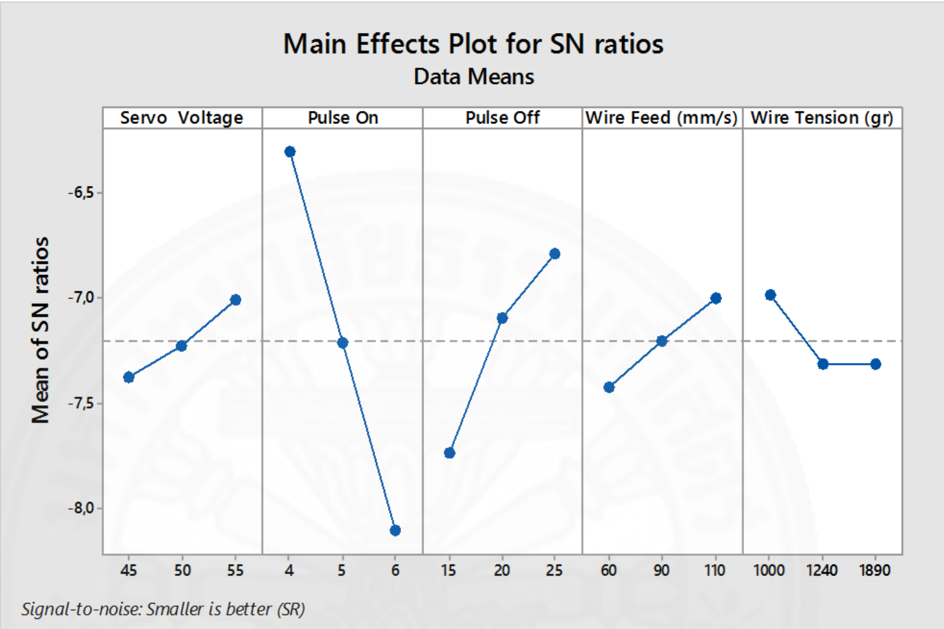


Figure 4.3 SN ratio SR (condition: single layer, square part)

Table 4.8 Response table of SR for square part with single layer case

Level	**Voltage**	**Pulse on**	**Pulse off**	**Wire feed**	**Wire tension**
1	2.34	2.073	2.444	2.354	2.245
2	2.317	2.293	2.273	2.323	2.334
3	2.256	2.546	2.195	2.245	2.334
Delta	0.084	0.047	0.25	0.109	0.089
Rank	5	1	2	3	4

Table 4.9 ANOVA table of SR for square part with single layer case

Source	DF	Adj SS	Adj MS	F -Value
Servo voltage	2	0.03414	0.01707	3.79
Pulse on	2	1.00888	0.50444	112.08
Pulse off	2	0.29318	0.14659	32.57
wire feed	2	0.05455	0.02728	6.06
Wire tension	2	0.04746	0.02373	5.27
Error	16	0.07201	0.0045	
total	26	1.51022		
Model Summary				
S	R-sq	R-sq (adj)	R-sq (pred)	
0.06709	95.23%	92.25%	86.42%	

4.1.4 Machining accuracy

Table 4.10 shows the result for the effect of machining parameters on accuracy at the condition of single layer and square shape sample. SN ratio plot for percentage deviation are drawn in Figure 4.4, indicting the variation of deviation from different inputs. According to Figure 4.4, the optimum accuracy can be achieved at the lowest level of servo voltage, the lowest level of pulse on time, the second level of pulse off time, the highest level of wire feed, and the highest level of wire tension. The contribution of the factors on the deviation are shown in Table 4.11. According to table 4.10, the highest contribution to the deviation are coming from the servo voltage factor, followed by pulse on factor, wire tension factor, pulse off factor and wire feed. A higher servo means a higher gap between the wire and the workpiece. However, at higher servo voltage, lower amount of discharge current are happened. Thus, increasing the servo will be followed by the increased of the shape deviation. Singh and Gerg, (2009) also found the similar phenomena in term of servo voltage. The pulse duration also affect the accuracy of the machining process of wire-EDM.

An increase in the pulse duration increases the shape deviation due to the high amount of discharge that lead to the rougher eroding process. Moreover, the wire tension also give a significant effect on the accuracy. The tougher tension of wire give more stability of the wire that lead to the lower deviation on the result obtained.

The ANOVA with the mean deviation at 98% confidence interval is given in Table 4.12. According to Table 4.11, the highest F-test value was from servo voltage factor (439.5), followed by pulse on time (17.96), wire tension (12.49), pulse off time (2.05), and wire feed (0.54), respectively. According to this obtains, the pulse off time factor and wire feed have given insignificant effect on the accuracy.

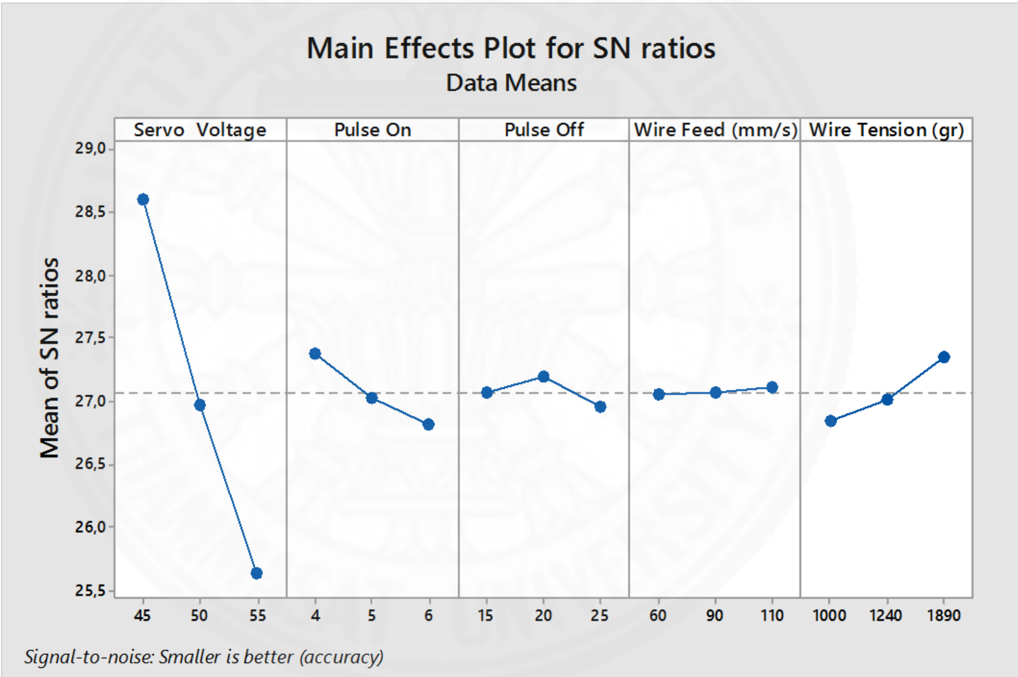


Figure. 4.4 SN ratio for machining accuracy (condition: single layer, square part)

Table 4.10 Machining accuracy for square part with single layer case

Servo Voltage	Pulse On	Pulse Off	Wire Feed (mm/s)	Wire Tension (gr)	Deviation
45	4	15	60	1000	3.80
45	4	15	60	1240	3.60
45	4	15	60	1890	3.40
45	5	20	90	1000	3.89
45	5	20	90	1240	3.69
45	5	20	90	1890	3.49
45	6	25	110	1000	4.00
45	6	25	110	1240	3.90
45	6	25	110	1890	3.70
50	4	20	110	1000	4.46
50	4	20	110	1240	4.26
50	4	20	110	1890	4.05
50	5	25	60	1000	4.65
50	5	25	60	1240	4.75
50	5	25	60	1890	4.34
50	6	15	90	1000	4.77
50	6	15	90	1240	4.65
50	6	15	90	1890	4.46
55	4	25	90	1000	5.11
55	4	25	90	1240	5.11
55	4	25	90	1890	5.11
55	5	15	110	1000	5.23
55	5	15	110	1240	5.23
55	5	15	110	1890	5.23
55	6	20	60	1000	5.32
55	6	20	60	1240	5.33
55	6	20	60	1890	5.32

Table 4.11 Response table of machining accuracy for square part with single layer case

Level	Servo Voltage	Pulse on	Pulse off	Wire feed	Wire tension
1	0.03718	0.04322	0.04486	0.04501	0.04581
2	0.04487	0.045	0.04423	0.04476	0.04502
3	0.05223	0.04519	0.04519	0.04451	0.04345
Delta	0.01506	0.00284	0.00096	0.0005	0.00235
Rank	1	2	4	5	3

Table 4.12 ANOVA table of machining accuracy for square part with single layer case

Source	DF	Adj SS	Adj MS	F -Value
Servo voltage	2	0.00102	0.00051	439.5
Pulse on	2	0.000037	0.000019	17.96
Pulse off	2	0.000004	0.000002	2.05
wire feed	2	0.000001	0.000001	0.54
Wire tension	2	0.000026	0.000013	12.49
Error	16	0.000017	0.000001	
total	26	0.001105		
Model Summary				
S	R-sq	R-sq (adj)	R-sq (pred)	
0.00102	98.50%	97.57%	95.74%	

4. 2 Square part with multiple layer case

4. 2. 1 Machining cost

Table 4.13 presented the results obtained from the multiple layer case strategy for the square part sample. According to Figure 4.5, with the same cutting parameters, doubling sample from single layer to double layer may give more efficient wire-EDM operation. Doubling the layer may give 20% up to 50% cost efficiency, regarding to the effectivity of the power and electrode usage.

Table 4.13 Machining cost for square part with multiple layer case

Servo Voltage	Pulse On	Pulse Off	Wire Feed (mm/s)	Wire Tension (gr)	Wire cost	Power cost	Total cost
45	4	15	60	1000	1.44	0.36	1.80
45	4	15	60	1240	1.42	0.35	1.77
45	4	15	60	1890	1.41	0.35	1.76
45	5	20	90	1000	1.88	0.32	2.19
45	5	20	90	1240	1.87	0.32	2.19
45	5	20	90	1890	1.86	0.32	2.19
45	6	25	110	1000	2.08	0.30	2.38
45	6	25	110	1240	2.08	0.30	2.38
45	6	25	110	1890	2.08	0.30	2.38
50	4	20	110	1000	3.02	0.44	3.46
50	4	20	110	1240	2.98	0.44	3.42
50	4	20	110	1890	2.97	0.43	3.40
50	5	25	60	1000	1.44	0.39	1.83
50	5	25	60	1240	1.42	0.39	1.81
50	5	25	60	1890	1.42	0.39	1.81
50	6	15	90	1000	1.55	0.31	1.86

50	6	15	90	1240	1.55	0.31	1.86
50	6	15	90	1890	1.55	0.32	1.86
55	4	25	90	1000	2.62	0.50	3.12
55	4	25	90	1240	2.58	0.49	3.07
55	4	25	90	1890	2.58	0.49	3.07
55	5	15	110	1000	1.96	0.34	2.30
55	5	15	110	1240	1.95	0.34	2.29
55	5	15	110	1890	1.90	0.34	2.23
55	6	20	60	1000	1.14	0.38	1.52
55	6	20	60	1240	1.13	0.38	1.52
55	6	20	60	1890	1.13	0.38	1.52

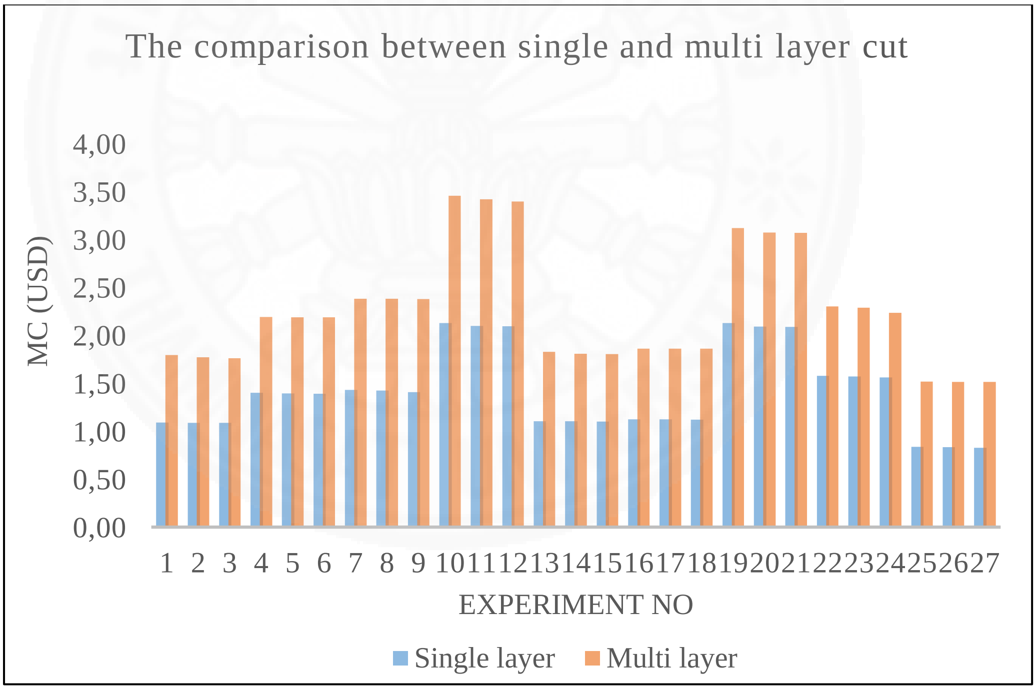


Figure 4.5 Machining cost comparison for square part sample

In order compare those two samples data and adequately see the difference, therefore 2 sample test (t-test) has been conducted. It compares two means data and to tell weather they are different from each other or not. The t test also to provide the degree significance the differences of the two samples data. Table 4.14 shows the two sample t-test results, it shows that the difference between two means sample data (machining cost of single layer and multiple layer) are statistically significant with p-value equal to 0.000 (P-value < α).

Table 4.14 Two-sample T-Test result for the machining cost of the square part sample

Two-sample T-Test and CI : Single layer; Multi Layer				
	N	Mean	stDev	SE Mean
Single layer	27	1.417	0.430	0.083
Multi Layer	27	2.260	0.608	0.120
Difference = μ (Single layer) - μ (Multi layer)				
Estimate for difference: -0.842				
95% CI for difference: (-1.131; -0.553)				
T-Test of difference = 0 (vs ≠): T-Value = -5.87 P-Value = 0.000 DF = 46				

4. 2. 2 Material Removal Rate (MRR)

Table 4.15 presented the results obtained from the multiple layer case strategy for the square part sample. According to Figure 4.6, with the same cutting parameters, doubling sample from single layer to double layer may give more efficient wire-EDM operation. Doubling the layer may increase the MRR up to 40% from the single layer case, regarding to the effectivity of the power and electrode usage. Table 4.16 shows the result of the two sample T-Test, it reveals that the difference between two samples data are statistically significant with p-value equal to

Table 4.15 MRR for square part with multiple layer case

Servo Voltage	Pulse On	Pulse Off	Wire Feed (mm/s)	Wire Tension (gr)	MRR
45	4	15	60	1000	0.151
45	4	15	60	1240	0.152
45	4	15	60	1890	0.154
45	5	20	90	1000	0.178
45	5	20	90	1240	0.178
45	5	20	90	1890	0.178
45	6	25	110	1000	0.201
45	6	25	110	1240	0.201
45	6	25	110	1890	0.201
50	4	20	110	1000	0.120
50	4	20	110	1240	0.121
50	4	20	110	1890	0.122
50	5	25	60	1000	0.141
50	5	25	60	1240	0.142
50	5	25	60	1890	0.143
50	6	15	90	1000	0.202
50	6	15	90	1240	0.203
50	6	15	90	1890	0.203
55	4	25	90	1000	0.102
55	4	25	90	1240	0.103
55	4	25	90	1890	0.103
55	5	15	110	1000	0.173
55	5	15	110	1240	0.174
55	5	15	110	1890	0.178
55	6	20	60	1000	0.167
55	6	20	60	1240	0.167
55	6	20	60	1890	0.167

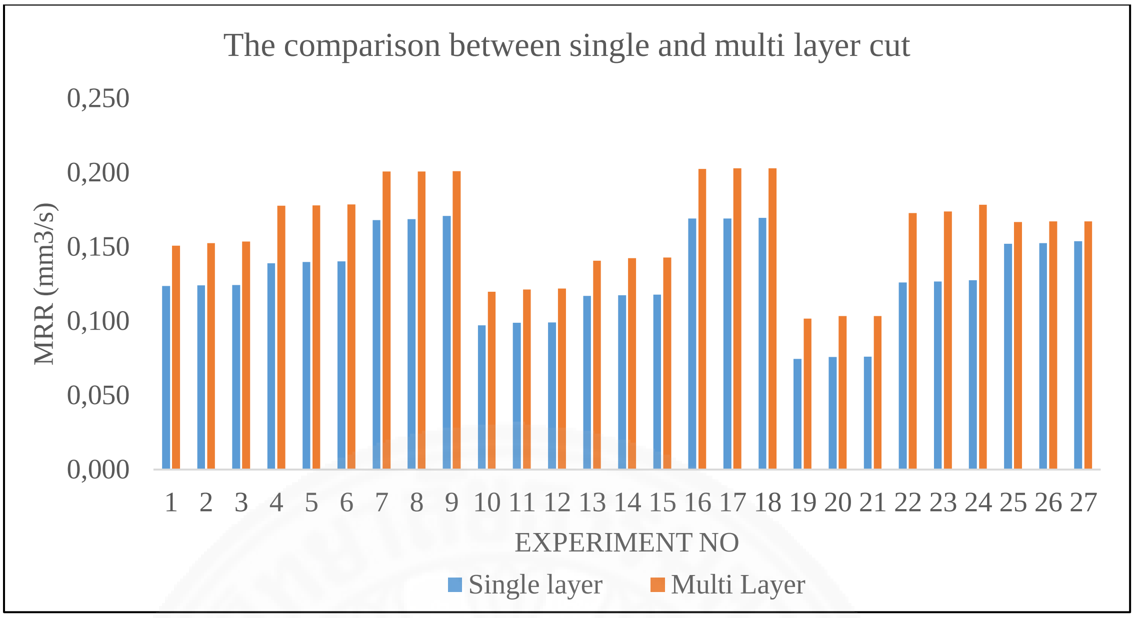


Figure 4.6 MRR comparison for square part sample

Table 4.16 Two-sample T-Test result for the MRR of the square part sample

Two-sample T-Test and CI : Single layer; Multi Layer				
	N	Mean	stDev	SE Mean
Single layer	27	0.130	0.030	0.006
Multi Layer	27	0.160	0.033	0.006
Difference = μ (Single layer) - μ (Multi layer)				
Estimate for difference: -0.842				
95% CI for difference: (-1.131; -0.553)				
T-Test of difference = 0 (vs ≠): T-Value = -5.87 P-Value = 0.000 DF = 46				

4. 2. 3 Surface Roughness (SR)

Table 4.17 presented the results of Surface roughness obtained from the multiple layer case strategy for the square part sample. According to Figure 4.7, with the same cutting parameters, doubling sample from single layer to double layer may not give any significant effect on the cut surface. It was not found any statistical difference for the SR between the single layer cut surface and multiple layer cut surface (Figure 4.7 and Table 4.18).

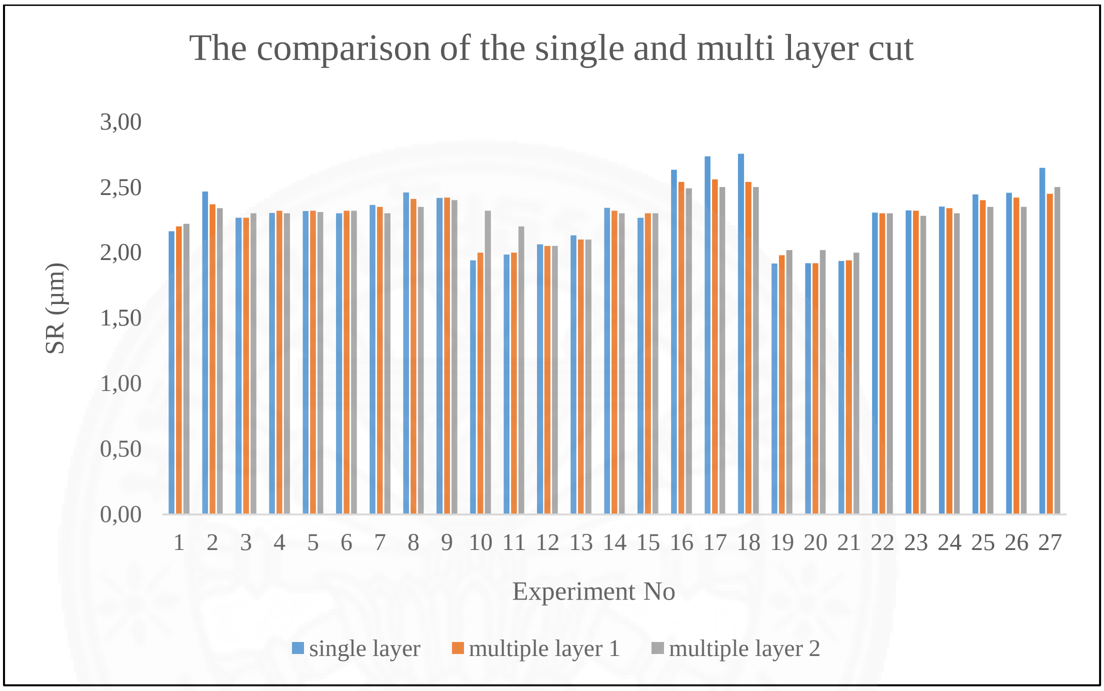


Figure 4.7 SR comparison for square part sample

Table 4.17 SR for square part with multiple layer case

Servo Voltage	Pulse On	Pulse Off	Wire Feed (mm/s)	Wire Tension (gr)	SR 1 (upper layer)	SR 2 (lower layer)
45	4	15	60	1000	2.20	2.22
45	4	15	60	1240	2.37	2.34
45	4	15	60	1890	2.27	2.30
45	5	20	90	1000	2.32	2.30
45	5	20	90	1240	2.32	2.31
45	5	20	90	1890	2.32	2.32
45	6	25	110	1000	2.35	2.30
45	6	25	110	1240	2.41	2.35
45	6	25	110	1890	2.42	2.40
50	4	20	110	1000	2.00	2.32
50	4	20	110	1240	2.00	2.20
50	4	20	110	1890	2.05	2.05
50	5	25	60	1000	2.10	2.10
50	5	25	60	1240	2.32	2.30
50	5	25	60	1890	2.30	2.30
50	6	15	90	1000	2.54	2.49
50	6	15	90	1240	2.56	2.50
50	6	15	90	1890	2.54	2.50
55	4	25	90	1000	1.98	2.02
55	4	25	90	1240	1.92	2.02
55	4	25	90	1890	1.94	2.00
55	5	15	110	1000	2.30	2.30
55	5	15	110	1240	2.32	2.28
55	5	15	110	1890	2.34	2.30
55	6	20	60	1000	2.40	2.35
55	6	20	60	1240	2.42	2.35
55	6	20	60	1890	2.45	2.50

Table 4.18 Two-Sample T-Test result for the SR of the square part sample

Two-sample T-Test and CI : Single layer; Multi Layer 1				
	N	Mean	stDev	SE Mean
Single layer	27	2.304	0.241	0.046
Multi Layer 1	27	2.276	0.188	0.036
Difference = μ (Single layer) - μ (Multi layer 1)				
Estimate for difference: 0.0280				
95% CI for difference: (-0.0902; 0.1463)				
T-Test of difference = 0 (vs ≠): T-Value = 0.48 P-Value = 0.636 DF = 49				
Two-sample T-Test and CI : Single layer; Multi Layer 2				
	N	Mean	stDev	SE Mean
Single layer	27	2.304	0.241	0.046
Multi Layer 2	27	2.286	0.144	0.028
Difference = μ (Single layer) - μ (Multi layer 2)				
Estimate for difference: 0.0182				
95% CI for difference: (-0.0907; 0.1272)				
T-Test of difference = 0 (vs ≠): T-Value = 0.34 P-Value = 0.737 DF = 42				
Two-sample T-Test and CI : Multi layer 1; Multi Layer 2				
	N	Mean	stDev	SE Mean
Multi Layer 1	27	2.276	0.188	0.036
Multi Layer 2	27	2.286	0.144	0.028
Difference = μ (Multi layer 1) - μ (Multi layer 2)				
Estimate for difference: -0.0098				
95% CI for difference: (-0.1015; 0.0818)				
T-Test of difference = 0 (vs ≠): T-Value = -0.22 P-Value = 0.830 DF = 48				

4.2.4 Machining accuracy

Table 4.19 presented the results of machining accuracy obtained from the multiple layer case strategy for the square part sample. According to Figure 4.8, with the same cutting parameters, doubling sample from single layer to double layer may not give any significant effect on the machining accuracy. It was not found any statistical difference for the machining deviation means between the single layer and multiple layer (Table 4.20).

Table 4.19 Machining accuracy for square part with multiple layer case

Servo voltage	Pulse On	Pulse Off	Wire Feed (mm/s)	Wire Tension (gr)	Deviation 1 (%) (upper layer)	Deviation 2 (%) (lower layer)
45	4	15	60	1000	3.50	3.50
45	4	15	60	1240	3.50	3.50
45	4	15	60	1890	3.40	3.40
45	5	20	90	1000	3.80	3.80
45	5	20	90	1240	3.70	3.70
45	5	20	90	1890	3.50	3.50
45	6	25	110	1000	4.00	4.00
45	6	25	110	1240	3.90	3.90
45	6	25	110	1890	3.90	3.90
50	4	20	110	1000	4.50	4.50
50	4	20	110	1240	4.40	4.40
50	4	20	110	1890	4.30	4.30
50	5	25	60	1000	4.50	4.50
50	5	25	60	1240	4.60	4.60
50	5	25	60	1890	4.20	4.20
50	6	15	90	1000	4.80	4.80
50	6	15	90	1240	4.80	4.80
50	6	15	90	1890	4.50	4.50
55	4	25	90	1000	5.00	5.00
55	4	25	90	1240	4.90	4.90
55	4	25	90	1890	4.90	4.90
55	5	15	110	1000	5.20	5.20
55	5	15	110	1240	5.20	5.20

55	5	15	110	1890	5.20	5.20
55	6	20	60	1000	5.00	5.00
55	6	20	60	1240	5.40	5.40
55	6	20	60	1890	5.10	5.10

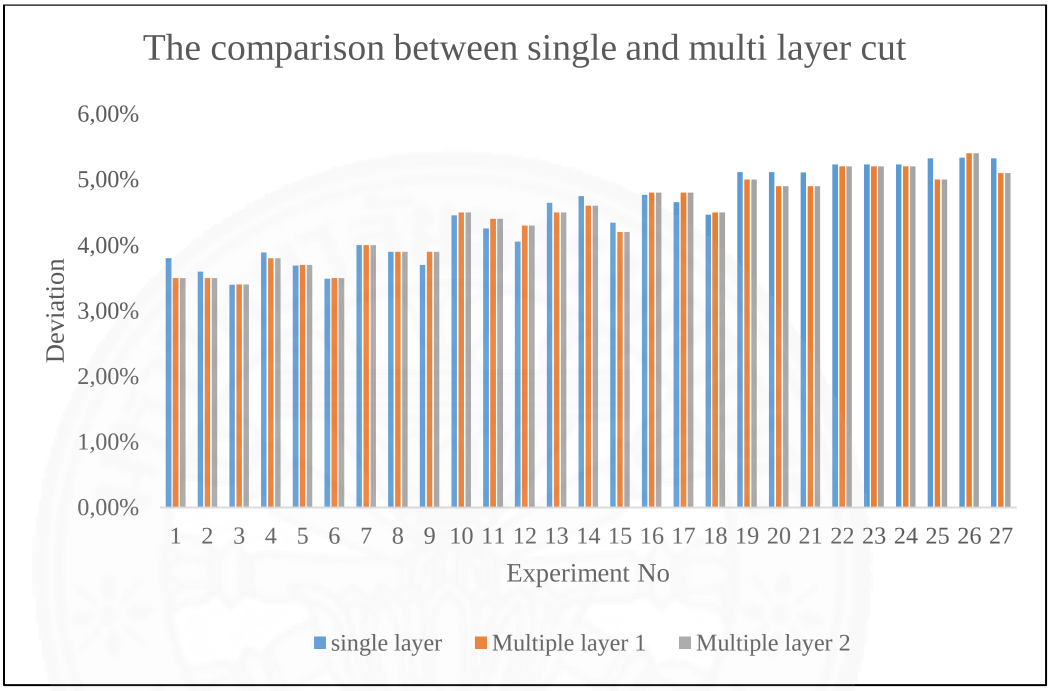


Figure 4.8 Deviation comparison for square part sample

Table 4.20 Two-Sample T-Test result for the Deviation of square part sample

Two-sample T-Test and CI : Single layer; Multi Layer 1				
	N	Mean	stDev	SE Mean
Single layer	27	0.04476	0.00652	0.0013
Multi Layer 1	27	0.04433	0.0062	0.0012
Difference = µ (Single layer) - µ (Multi layer 1)				
Estimate for difference: 0.00043				
95% CI for difference: (-0.00305; 0.00390)				

T-Test of difference = 0 (vs ≠): T-Value = 0.25 P-Value = 0.806 DF = 51				
Two-sample T-Test and CI : Single layer; Multi Layer 2				
	N	Mean	stDev	SE Mean
Single layer	27	0.04476	0.00652	0.0013
Multi Layer 2	27	0.04433	0.0062	0.0012
Difference = μ (Single layer) - μ (Multi layer 2)				
Estimate for difference: 0.00043				
95% CI for difference: (-0.00305; 0.00390)				
T-Test of difference = 0 (vs ≠): T-Value = 0.25 P-Value = 0.806 DF = 51				
Two-sample T-Test and CI : Multi layer 1; Multi Layer 2				
	N	Mean	stDev	SE Mean
Multi Layer 1	27	0.04433	0.0062	0.0012
Multi Layer 2	27	0.04433	0.0062	0.0012
Difference = μ (Multi layer 1) - μ (Multi layer 2)				
Estimate for difference: 0.000				
95% CI for difference: (-0.00338;0.00338)				
T-Test of difference = 0 (vs ≠): T-Value = 0.00 P-Value = 1.00 DF = 52				

4. 3 Machining cost vs MRR

Figure 4.9 shows the relation between MRR and machining cost. In the high MRR, the machining cost can be reduced. However, according to figure 4.9, an increase in MRR can decrease the Cm only to some extent and then further increases the cost. At MRR 0.08 up to 0.16 mm3/s, the MC is significantly decrease from USD2.4 up to USD1.0, and from 0.16 to 0.18, the MC then increase again. This phenomena may happen because of the different type machining cost, which can be from the wire cost and power cost. For the wire-EDMing process, the major cost has come from the wire consumption, and slightly from the power cost. However, the significant factor that highly affect to the MRR was the machining power, such as pulse and servo voltage, which only a small effect from the wire feed and tension. Thus, at the low MRR condition, it is possible that the machine time increases so as the amount of wire electrode consumed increases, thus increasing the Cm. Moreover, at high MRR (0.16-0.18), the machining power has been increase and dominate the Cm at high MRR conditions, while the wire feed at the low setup level. Thus, the Cm has been increased after 0.16 to 0.18 of MRR.

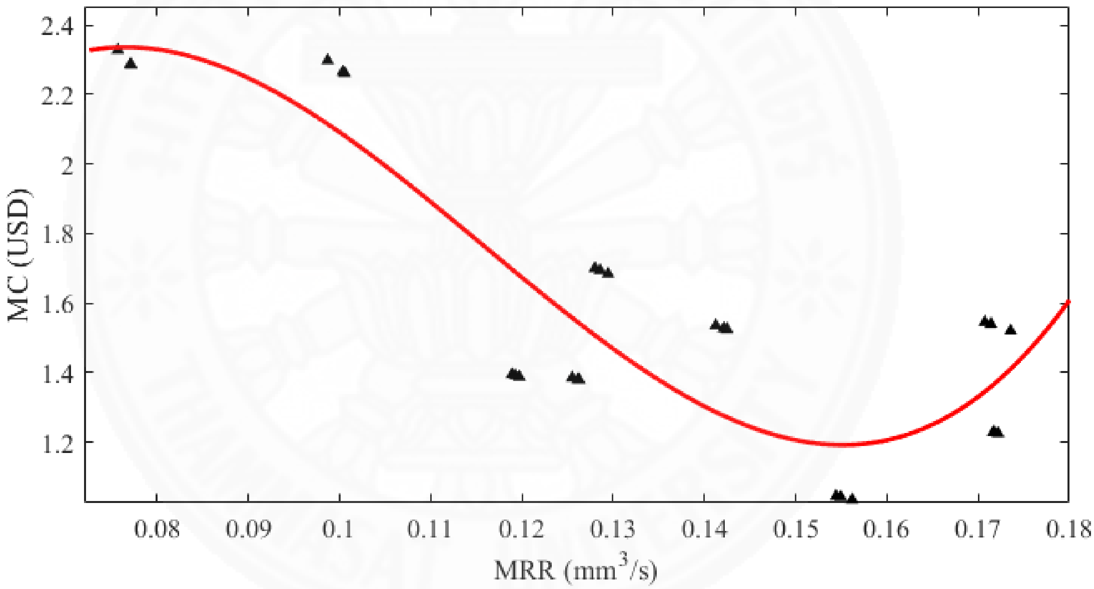


Figure 4.9 MRR vs Machining cost

4. 4 Machining cost vs SR

Figure 4.10 presented the relation between the machining cost and surface roughness. It indicated that the lower surface roughness required the higher machining cost. since the machining cost were from the power usage and wire expense, therefore the relation between machining cost and surface roughness will be based on the power relation to the roughness, along with wire feed relation to surface roughness. With higher pulse on time resulted in higher surface roughness due to higher thermal energy produced that lead to deeper craters on surface material.

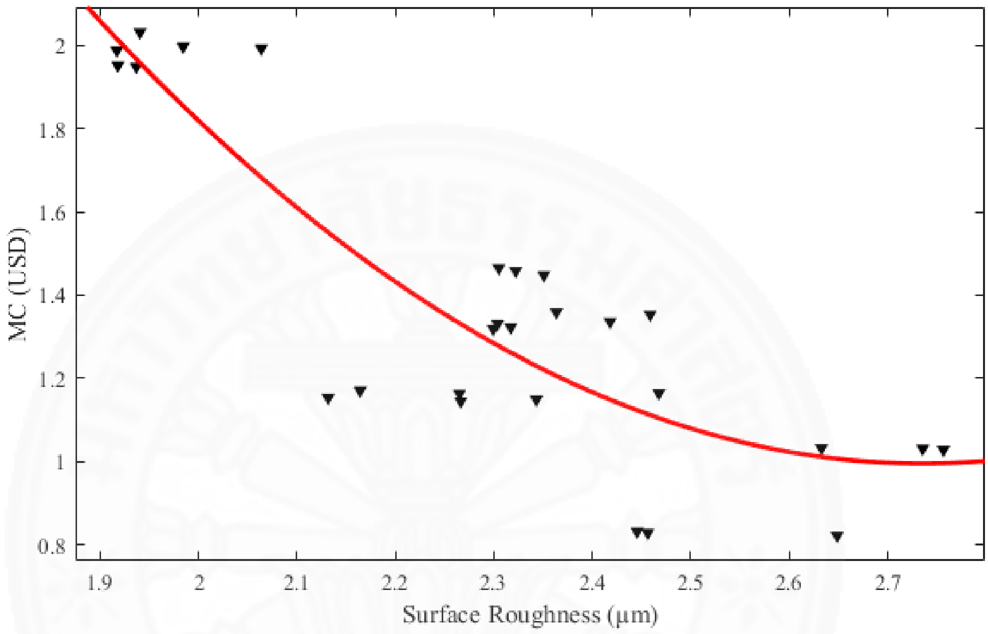


Figure 4.10 SR vs machining cost

Wire feed and wire tension are other significant factor to influence surface roughness. The increase in wire feed, reduced the surface roughness. Increasing wire feed means the faster the renewing and recovering process during wire-EDMing process. The faster wire feeding can increase effectivity of wire as the medium transfer of current, which may increase the stability of sparking process. Therefore, it produces smaller crater on the affected area. As the result, in higher wire feed caused a better surface. therefore, reducing the machining cost (reduce the wire feed) may increase the surface roughness. This results has been correspondent to the finding from Fard et al. (2013) in wire-EDMig investigation on Al-SiC metal matrix composite (MMC).

4. 5 Gear part case

In order to study the contribution of path angle contour in the wire-EDMing operation, therefore the machining process of wire-EDM also has been conducted on the gear part. Table 4. 21 presented the results obtained for the MRR and Machining cost for both single layer and multiple layer case.

Table 4.21 MRR and machining cost for gear part case

					MRR		Machining cost	
Servo Voltage	Puls e On	Puls e Off	Wire Feed (mm/s)	Wire Tension (gr)	Single layer	Multipl e layer	Single layer	Multipl e layer
45	4	15	60	1000	0.05	0.08	2.462	3.397
45	4	15	60	1240	0.05	0.08	2.478	3.395
45	4	15	60	1890	0.05	0.08	2.479	3.395
45	5	20	90	1000	0.05	0.08	3.218	3.875
45	5	20	90	1240	0.05	0.08	3.215	3.875
45	5	20	90	1890	0.05	0.08	3.211	3.872
45	6	25	110	1000	0.05	0.08	3.675	4.382
45	6	25	110	1240	0.05	0.08	3.668	4.380
45	6	25	110	1890	0.05	0.08	3.664	4.373
50	4	20	110	1000	0.04	0.07	3.927	4.675
50	4	20	110	1240	0.04	0.07	3.928	4.670
50	4	20	110	1890	0.04	0.07	3.928	4.670
50	5	25	60	1000	0.05	0.09	2.457	3.337
50	5	25	60	1240	0.05	0.09	2.457	3.336
50	5	25	60	1890	0.05	0.09	2.452	3.336
50	6	15	90	1000	0.05	0.08	3.169	3.816
50	6	15	90	1240	0.05	0.08	3.166	3.814
50	6	15	90	1890	0.05	0.08	3.163	3.809
55	4	25	90	1000	0.05	0.08	3.381	4.047

55	4	25	90	1240	0.05	0.08	3.382	4.043
55	4	25	90	1890	0.05	0.08	3.382	4.040
55	5	15	110	1000	0.04	0.07	3.912	4.653
55	5	15	110	1240	0.04	0.07	3.916	4.638
55	5	15	110	1890	0.04	0.07	3.916	4.638
55	6	20	60	1000	0.06	0.10	2.389	3.240
55	6	20	60	1240	0.06	0.10	2.386	3.247
55	6	20	60	1890	0.06	0.10	2.387	3.244

According to Figure 4. 11 and 4.12, the number of the angles may highly determine the machining performance of wire-EDM. The angle contour in the machining process of wire-EDM reduce the cutting speed, not only in the single layer but also in multiple layer case. Therefore, when doubling the layer of the workpiece, the MRR will be significantly increase. The effect of the machining parameters on cutting speed when the electrode pass through the angle contour is not found to be significant, it was much different when cutting the square part sample, the performance of the wire-EDM are based on the electrical power and wire feed. Also, an increase in machining cost from single layer to multi layer was not found to be significant. Thus, the machining cost in multi layer strategy for each product will be lower compare to the single layer cut.

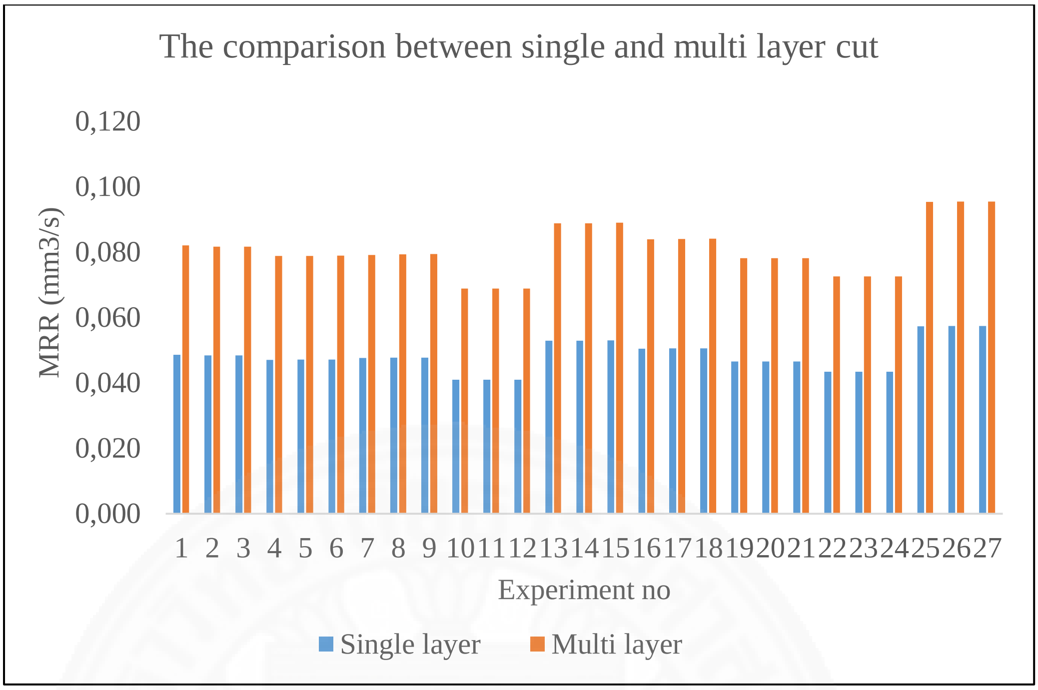


Figure 4.11 MRR comparison for gear part case

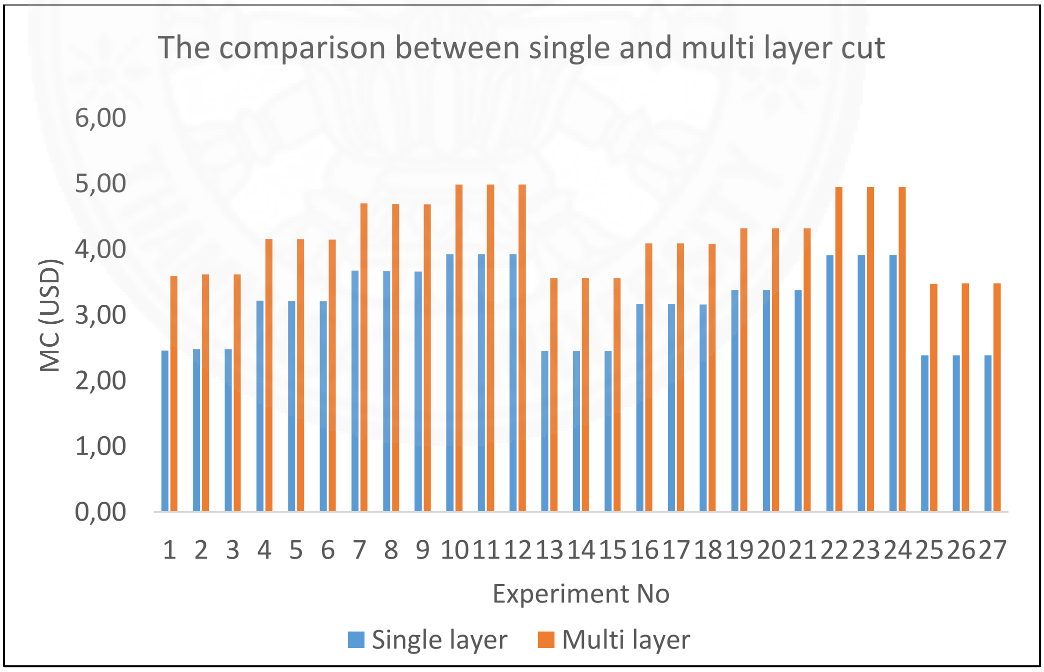


Figure 4.12 Machining cost comparison for gear part case

4. 6 Multiple objective optimization using utility concept

The utility concept was utilized to conduct the multiple objective optimization process. Eq. 13-17 were used to calculate the preference utility number of the individual characteristic and overall utility. The SN ratio value of each response were used as the input value for each characteristics as quantified by using eq. 5-6. In this case, square part sample with both single multi layer case were used for be the input data.

4.6. 1 Single layer cut

For the single layer data, Table 4.22 shows that the highest overall utility gained from the experiment was from the experiment no. 3 by using the lowest level of servo voltage, the lowest level of pulse on time, the lowest level of pulse off time, the lowest level of wire feed and the highest level of wire tension.

Table 4.22 Utility calculation results of the single layer cut

No	Individual Utility				Overall Utility
	Cm	MRR	SR	D	
1	3.24	5.06	5.62	6.88	5.20
2	3.28	5.12	2.36	7.92	4.67
3	3.28	5.13	4.35	9.00	5.44
4	1.58	6.42	4.03	6.43	4.62
5	1.61	6.49	3.82	7.45	4.84
6	1.62	6.53	4.03	8.51	5.17
7	1.48	8.78	3.41	5.89	4.89
8	1.50	8.84	2.45	6.39	4.79
9	1.56	9.00	2.82	7.41	5.20
10	0.00	2.52	8.68	3.74	3.73
11	0.04	2.69	8.06	4.67	3.86
12	0.05	2.71	6.92	5.62	3.82
13	3.13	4.47	6.00	2.89	4.12
14	3.15	4.50	3.61	2.45	3.43
15	3.17	4.54	4.35	4.25	4.08
16	2.99	8.85	0.99	2.36	3.80
17	2.99	8.86	0.15	2.86	3.71
18	3.01	8.90	0.00	3.70	3.90
19	0.00	0.00	9.00	0.89	2.47
20	0.05	0.16	9.00	0.90	2.53
21	0.05	0.17	8.68	0.90	2.45
22	1.04	5.28	3.92	0.40	2.66
23	1.06	5.33	3.82	0.41	2.65
24	1.08	5.41	3.51	0.41	2.60
25	8.42	7.50	2.54	0.04	4.63
26	8.55	7.55	2.45	0.00	4.64
27	9.00	7.65	0.83	0.05	4.38

4.6. 2 Multi layer cut

Table 4.23 shows overall overall utility obtained from the experiment. In order to get the equal weight for every response, therefore the weight for Mc is equal to 0.25, MRR equal to 0.25, while SR1, SR2, Deviation 1 and deviation 2 are equal to 0.125. The result shows that the experiment no. 1 by using the lowest level of servo voltage, the lowest level of pulse on time, the lowest level of pulse off time, the lowest level of wire feed and the lowest level of wire tension results the highest overall utility. It is a little bit different from the single layer cut, which give the highest level of wire tension as the optimum setup parameters. It was due to the low contribution of the wire tension in the machining operation, an increase in wire tension only give a small difference in the wire-EDM performance.

Table 4.23 Utility calculation results of the multiple layer cut

No	Individual Utility						Overall Utility
	Mc	MRR	SR1	SR2	Deviation 1	Deviation 2	
1	6.18	4.73	4.33	4.48	8.47	8.47	5.95
2	6.38	4.88	2.11	2.42	8.47	8.47	5.50
3	6.46	4.98	3.44	3.08	9.00	9.00	5.92
4	3.77	6.99	2.73	3.08	6.95	6.95	5.15
5	3.78	7.02	2.73	2.91	7.45	7.45	5.27
6	3.79	7.07	2.73	2.74	8.47	8.47	5.52
7	2.93	8.84	2.35	3.08	5.99	5.99	5.12
8	2.93	8.83	1.64	2.25	6.47	6.47	5.04
9	2.95	8.85	1.52	1.47	6.47	6.47	4.94
10	0.00	1.85	7.50	2.74	3.71	3.71	2.67
11	0.07	2.00	7.50	4.85	4.15	4.15	3.10
12	0.12	2.07	6.64	7.87	4.60	4.60	3.51
13	5.92	3.83	5.83	6.81	3.71	3.71	4.94

14	6.07	3.97	2.73	3.08	3.27	3.27	4.05
15	6.11	4.01	2.98	3.08	5.05	5.05	4.55
16	5.68	8.96	0.21	0.14	2.42	2.42	4.31
17	5.69	8.99	0.00	0.00	2.42	2.42	4.28
18	5.69	9.00	0.21	0.00	3.71	3.71	4.63
19	0.71	0.00	7.86	8.54	1.59	1.59	2.63
20	0.82	0.17	9.00	8.54	2.00	2.00	2.94
21	0.82	0.18	8.61	9.00	2.00	2.00	2.95
22	3.27	6.59	2.98	3.08	0.79	0.79	3.42
23	3.32	6.68	2.73	3.42	0.79	0.79	3.46
24	3.57	7.05	2.48	3.08	0.79	0.79	3.55
25	8.95	6.09	1.75	2.25	1.59	1.59	4.66
26	8.99	6.14	1.52	2.25	0.00	0.00	4.25
27	9.00	6.13	1.18	0.00	1.19	1.19	4.23

Then, the validity experiment was conducted to assess the model prediction obtained from the Taguchi's method. Also to see, the weather the study can give the machining improvement or not. Table 4.24 shows the model prediction results and the validity experiment result for both the initial setup and optimized setup.

Table 4.24 The comparison between the predicted and validity experiment (single layer cut)

Response	Predicted		Validation	
	Initial Stage (SV2, Ton1, Toff1, WF1, WT1)	Optimized Stage (SV1, Ton1, Toff1 WF1, WT3)	Initial Stage (SV2, Ton1, Toff1, WF1, WT1)	Optimized Stage (SV1, Ton1, Toff1 WF1, WT3)
Cm (USD)	1.241	1.083	1,141	1,092
MRR (mm3/s)	0.107	0.124	0,112	0,124
Ra (µm)	2.217	2.328	2,332	2,330
D (%)	4.470	3.460	4.450	3.470

4. 7 Micrograph analysis

Table 4.25 presented the different effect of the initial parameter and optimized parameter of the experimental results. It shows that the optimized parameters cut surface is much rougher than the initial stage due to the lower SV. It reveals that the optimized stage surface morphology has the wider and deeper crater than the initial stage cut surface. The lower SV give more discharge in the machining process, therefore, it may cause more crater and rougher surface. Also, the higher tension of the wire (optimized stage) may affect the surface roughness. This result was similar to the SN ratio table of the surface roughness (Figure 4.3), it specified that the higher the servo voltage, the lower the roughness (better surface gained), also the higher the tension the higher the roughness. Table 4.26 presented the effect of lowest level and highest level of servo voltage. It shows that the increase in SV may increase the cut surface roughness. Table 4.27 presented the effect of lowest level and highest level of pulse on time, showing that the increase in pulse on time give rougher cut surface. It was due to the higher power induced into the machining process. However, an increase in pulse off time, reduce the sparks due to the higher resting time during the process, and therefore reduce the surface cut (Table 4.28). The similar finding also obtained in figure 4.3, the pulse on time give the positive effect to the roughness, while pulse off time give negative effect. Moreover, an increase in wire feed and wire tension, can give more stability to the machining process, which may reduce the wire breakage. Also, the more stable machining process may reduce the crater on the surface cut (Figure 4.29 and 4.30).

Table 4.25 The comparison between (A) the initial stage and (B) optimized stage

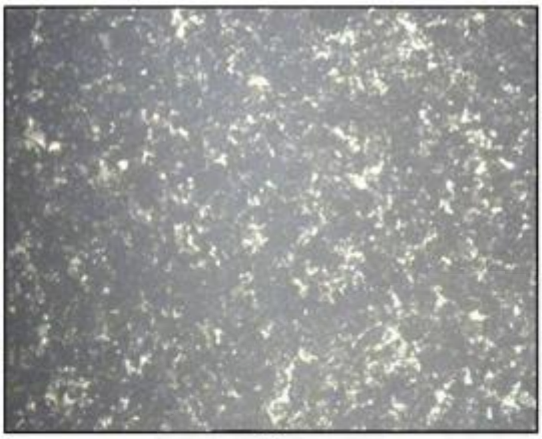
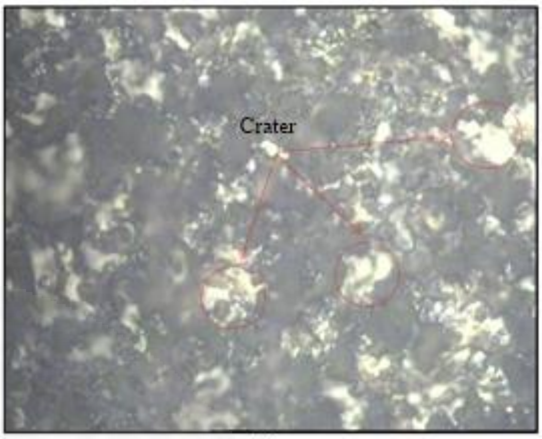
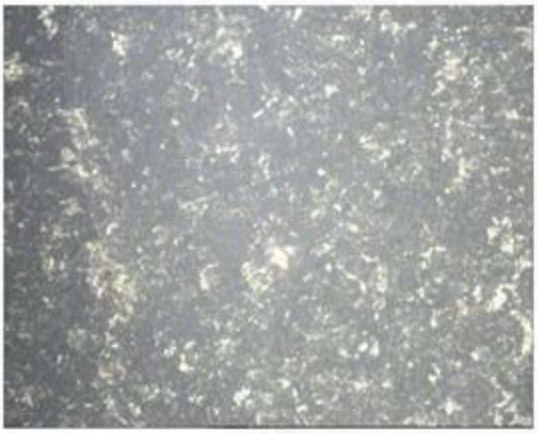
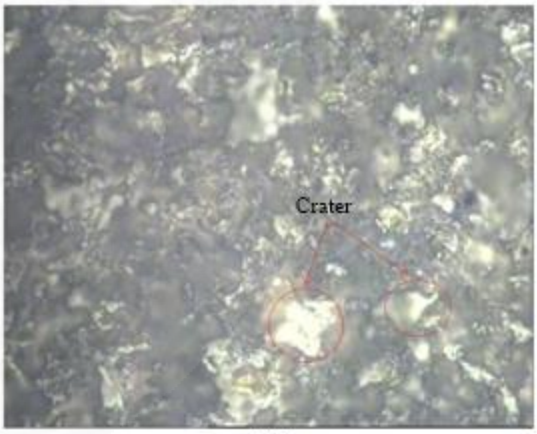
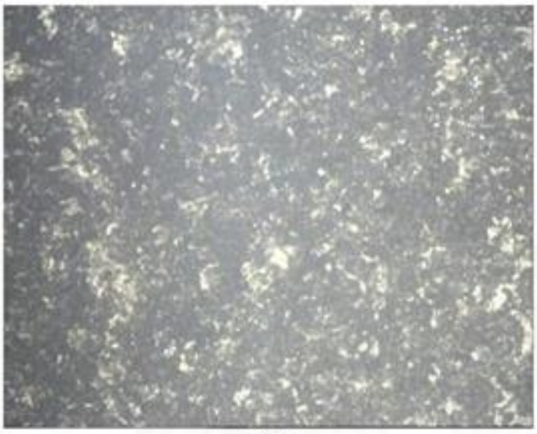
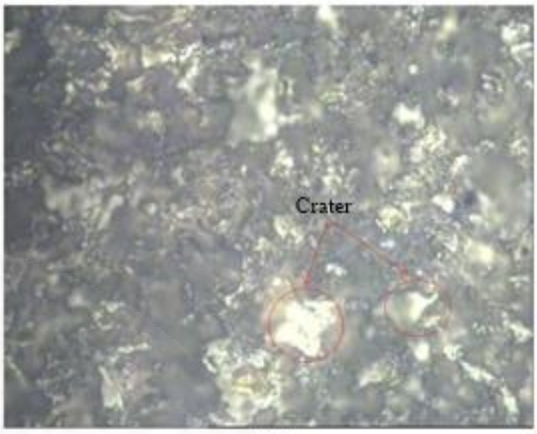
(SV2, Ton1, Toff1, WF1, WT1**)**
 20x  50x **A**
(SV1, Ton1, Toff1 WF1, WT3**)**
 20x  50x **B**

Table 4.26 The comparison between (A) the lowest and (B) the highest of SV

(SV1, Ton1, Toff1 WF1, WT3**)**



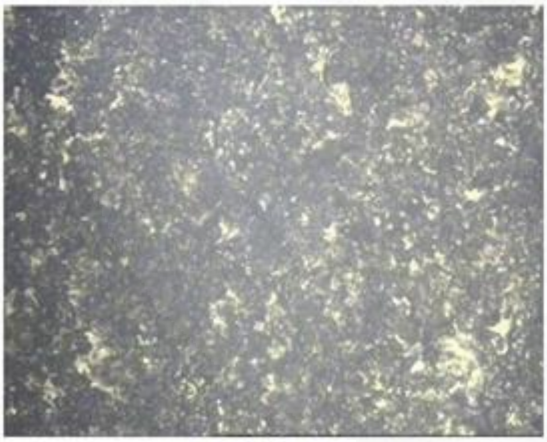
20x



50x

A

(SV3, Ton1, Toff1 WF1, WT3**)**



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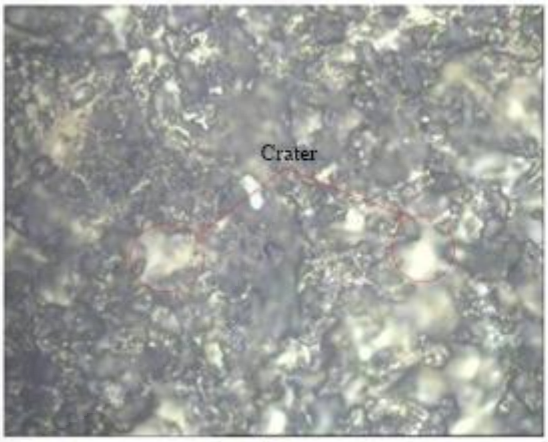


50x

B

Table 4.27 The comparison between (A) the lowest and (B) the highest of Ton

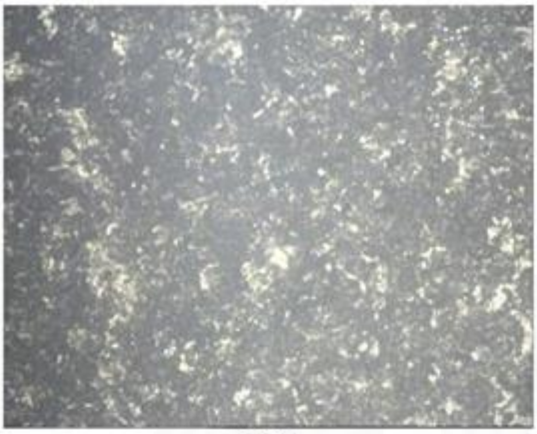
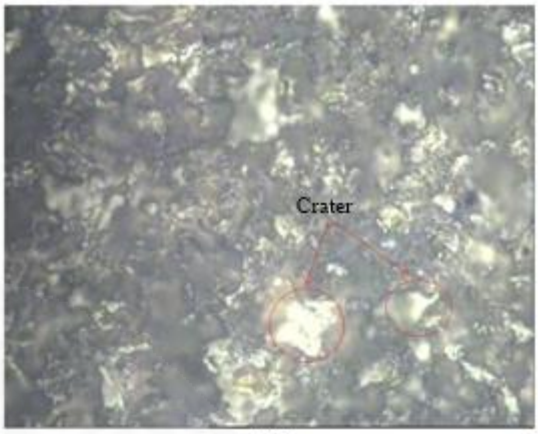
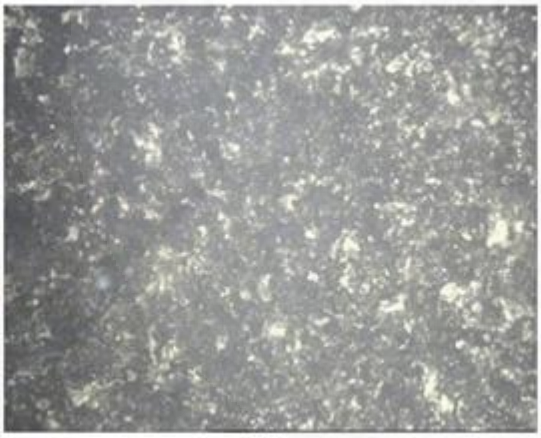
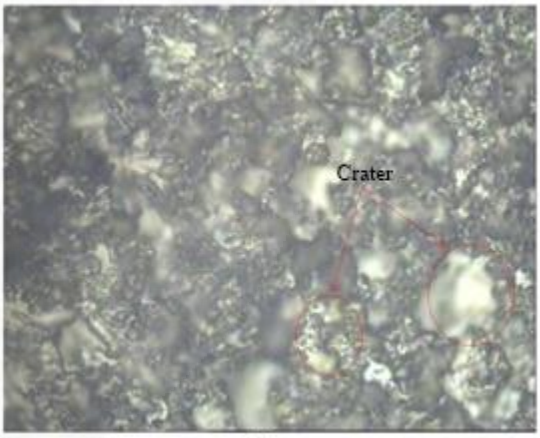
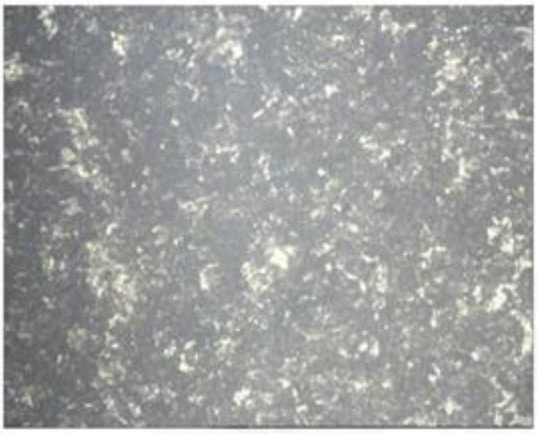
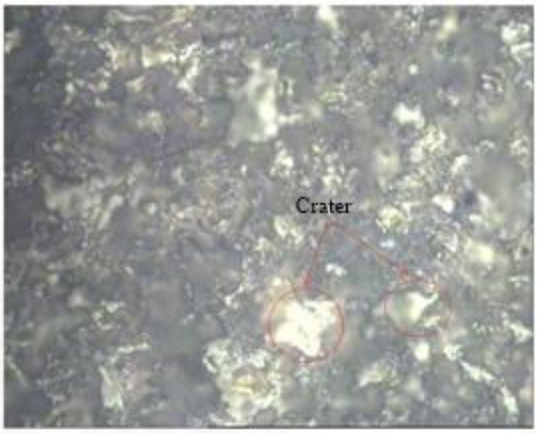
(SV1**, Ton1**, Toff1 WF1, WT3**)**
 20x  50x
A
(SV1, **Ton3**, Toff1 WF1, WT3**)**
 20x  50x
B

Table 4.28 The comparison between (A) the lowest and (B) the highest of Toff

(SV1, Ton1, **Toff1**, WF1, WT3**)**



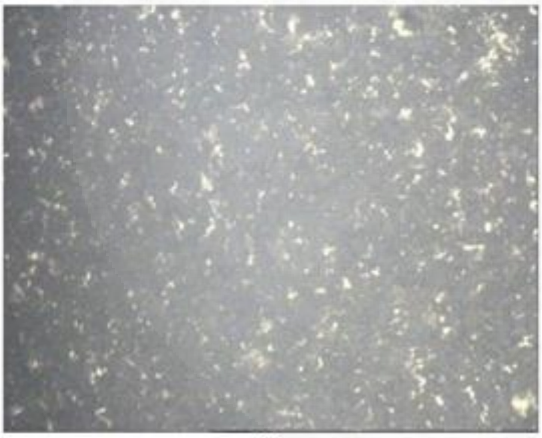
20x



50x

A

(SV1, Ton1, **Toff3**, WF1, WT3**)**



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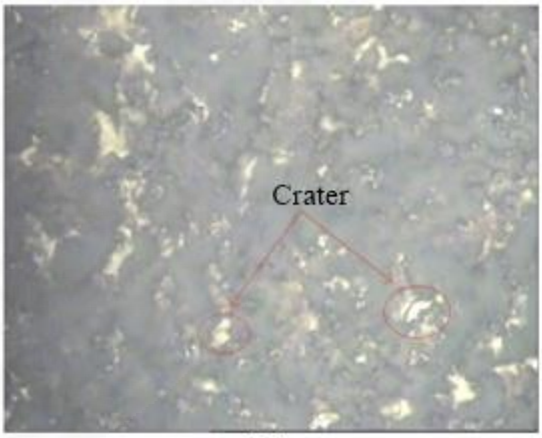
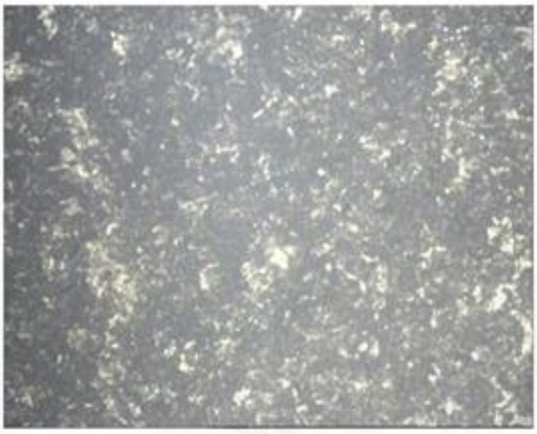


50x

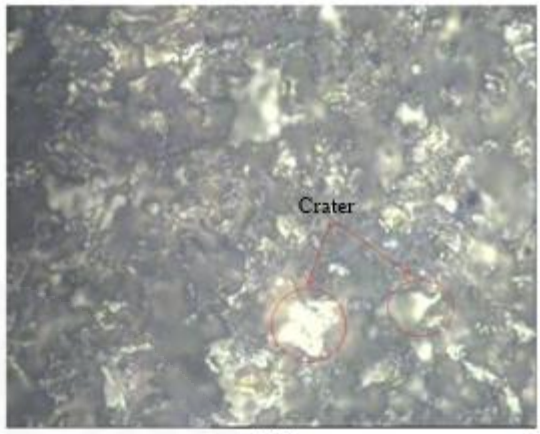
B

Table 4.29 The comparison between (A) the lowest and (B) the highest WF

(SV1**,** Ton1, Toff1 **WF1**, WT3**)**



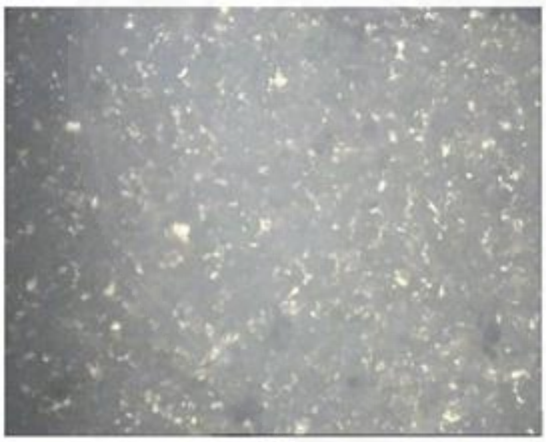
20x



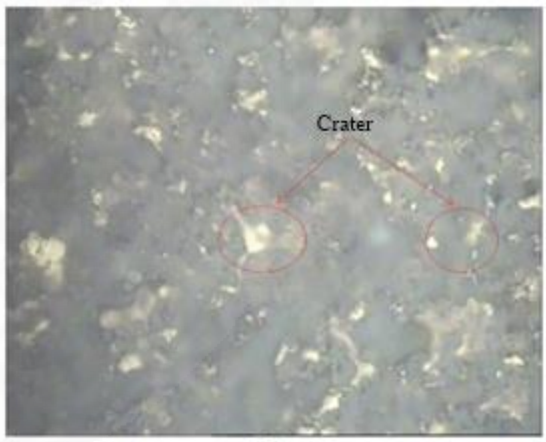
50x

A

(SV1**,** Ton1, Toff1, **WF3**, WT3**)**



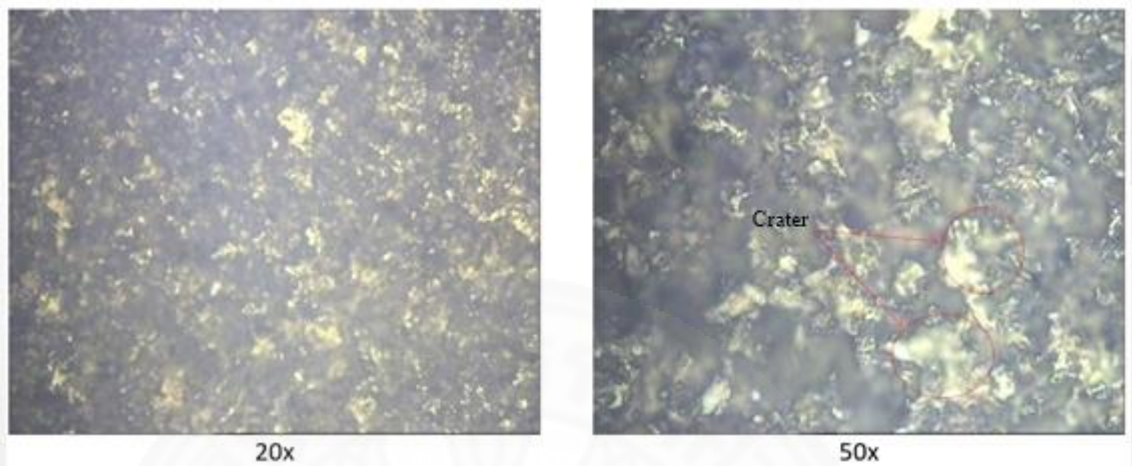
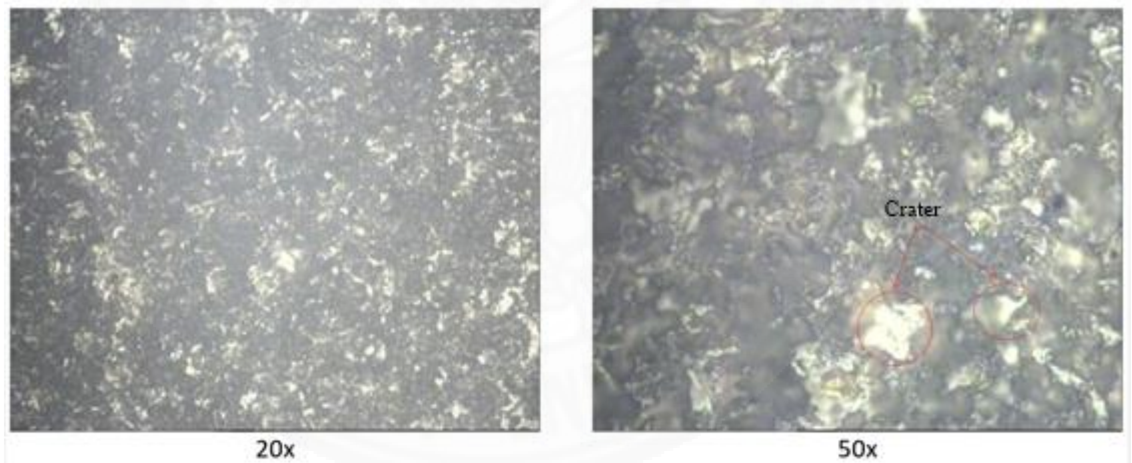
20x



50x

B

Table 4.30 The comparison between (A) the lowest and (B) the highest WT

(SV1**,** Ton1, Toff1 WF1, **WT1)**
 **A**
(SV1**,** Ton1, Toff1, WF1, **WT3)**
 **B**

Chapter 5
Conclusions and recommendations

5.1 Conclusions

In the present work, various experiment has been carried out in order to study the effect of wire-EDMing parameters on several output performances namely, machining cost, MRR, surface roughness, and machining accuracy. There are five parameters to be considered which are servo voltage, pulse on time, pulse off time, wire feed, and wire tension. The machining cost analysis has been presented in term of its relation to the other machining output. In order to reduce the machining cost and increase the wire-EDMing performances, a multiple layer cutting operation has been conducted. There are four case studies have been performed on the wire-EDM operation: *(1) square part with single layer, (2) square part with multiple layer, (3) gear part with single layer,* and *(4) gear part with multiple layer*. The accuracy of the finished parts obtained from the single and multiple-layers wire-EDMing operation were presented and discussed. The multiple layer cutting strategy presented more efficient cutting process with insignificant effect on other cut quality. The power has been played as the important factor for controlling the cutting parameters; for the straight cutting direction (i.e., square-shape model), increasing the value of power will have direct effect on the cutting speed which keeps increasing relatively. In contrast, for multi-angle contour model, the cutting speed decreases for supporting the edge-profile shape even the value of power is adjusted to be in the higher level. Cutting with fast speed might not maintain the shape as sharp edge or contour, the machine decides itself automatically to reduce the scale of cutting speed.

The multiple objective optimization process by using Taguchi's utility concept was presented in order to get the optimum performance of wire-EDM with respect to all interested responses, including machining cost, MRR, surface roughness, and machining accuracy. Additionally, the micrograph analysis was provided in order to visualize the effect of each machining parameters on the cut surface.

5.2 Findings

The significances of this experiment can be drawn as follows:

1. Electrical power adjusted for the machining process namely, servo voltage and pulse ON/OFF time, can give the significant influence on the machining output (i.e., machining cost, MRR, and surface roughness).
2. The study obtained a higher material removal rate and surface roughness can be obtained when higher power is applied
3. The wire feed value has been found to be the major expense on the machining cost, followed by servo voltage, the pulse on time and pulse off time. Moreover, wire tension found to be significant in order to increase the eroding stability.
4. The optimum cutting speed of wire-EDMing process was at the second level of servo voltage (SV_2), highest level of pulse on time (Ton_3), lowest level of pulse off time ($Toff_1$), lowest level of wire feed (WF_1) and the lowest level of wire tension (WT_1).
5. The optimum condition of the surface roughness was at the lowest level of servo voltage (SV_2), lowest level of pulse on time (Ton_3), highest level of pulse off time ($Toff_1$), highest level of wire feed (WF_1) and the lowest level of wire tension (WT_1).
6. The obtained optimum servo voltage, pulse on time, pulse off time, wire feed and wire tension were 55 V, 6 μs, 20 μs, 80 mm/s and 1390 g, respectively. With this condition, 0.19 mm, 3/s material removal rate, 2.55 μm surface roughness and 5.4% deviation can be obtained with 1.04 USD of machining cost. With the optimum parameter, MRR can be increased and machining cost can is reduced, while surface roughness is decreased.

5.3 Recommendations

There are several recommendations according to this study:

1. Since, the machining process of wire-EDM was very stochastic and various parameters very influence on the machining performance. Thus, the results obtained from one experiment may be different to other experiment because of unconditionally environmental factor such as dielectric conductivity degradation and the temperature instability. Therefore, the study with focused on the thermal modeling process is needed to be considered in order to provide clearer effect of the machining parameters on the machining performance.
2. In the present work, the multiple layer cutting strategy was performed only with 2 layers and this presented a very significant effect on the machining efficiency. Therefore, more investigations on this issue needs to be considered in order to increase not only the output characteristics but also the machining efficiency and effectivity such as by considering several material thickness as the influence factor.
3. For the utility concept issue, the weight of each response was adjusted by the author. Therefore, it is need to consider to combine a utility concept with AHP technique in order to get the reliable weight for each response.

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Appendix A. NC File for square part sample

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( SQUARE PART )
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N110 G92 X0. Y0. I100. J0.
N120 G0 X0. Y0.
N130 M60
N140 M35
N150 M81
N160 S157 D1
N170 G41 G1 Y3.
N180 X-5.
N190 Y13.
N200 X5.
N210 Y3.
N220 X0.
N230 G40 Y0.
N240 M50
N250 M30
%
```

Appendix B. NC File for gear sample

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N110 G92 X0. Y0. I100. J0.
N120 G0 X0. Y0.
N130 M60
N140 M35
N150 M81
N160 S157 D1
N170 G41 G1 Y2.
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N190 X-.2497 Y2.0311 I1.6897 J1.2659
N200 X-.2651 Y2.0524 I1.6726 J1.2205
N210 X-.2802 Y2.0739 I1.6713 J1.1873
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N230 X-.3091 Y2.117 I1.6496 J1.1091
N240 X-.323 Y2.1385 I1.6285 J1.0644
N250 X-.3366 Y2.1602 I1.6244 J1.0314
N260 X-.3497 Y2.1818 I1.6014 J.9871
N270 X-.3625 Y2.2036 I1.5958 J.9544
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N290 X-.387 Y2.2471 I1.5635 J.8779
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N330 X-.4312 Y2.3344 I1.4872 J.7274
N340 X-.4412 Y2.3561 I1.4546 J.6852
N350 X-.451 Y2.378 I1.4426 J.6535
N360 X-.4602 Y2.3997 I1.4074 J.612
N370 X-.4692 Y2.4216 I1.3935 J.5807
N380 X-.4776 Y2.4433 I1.3552 J.54
N390 X-.4857 Y2.4652 I1.3394 J.509
N400 X-.4933 Y2.4868 I1.2977 J.4691
N410 X-.5006 Y2.5087 I1.2797 J.4388
N420 X-.5074 Y2.5302 I1.2342 J.3998
N430 X-.5138 Y2.552 I1.2139 J.37
N440 X-.5197 Y2.5734 I1.1642 J.3322
N450 X-.5252 Y2.5951 I1.1411 J.3031
N460 X-.5302 Y2.6164 I1.0863 J.2666
N470 X-.5349 Y2.6381 I1.06 J.2383
N480 X-.5389 Y2.6591 I.9994 J.2033
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N510 X-.5483 Y2.7231 I.8659 J.117
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N1940 X-2.8349 Y6.2532 I.5753 J-1.7682
N1950 X-2.811 Y6.2605 I.5382 J-1.7337
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N5420 X1.8308 Y3.1155 I.4423 J1.307
N5430 X1.8092 Y3.1234 I.4549 J1.274
N5440 X1.7882 Y3.1316 I.457 J1.2143
N5450 X1.7671 Y3.1401 I.4675 J1.1797
N5460 X1.7467 Y3.1489 I.4661 J1.1173
N5470 X1.7262 Y3.1581 I.4745 J1.081
N5480 X1.7065 Y3.1674 I.469 J1.0155
N5490 X1.6867 Y3.1773 I.4747 J.9774
N5500 X1.6677 Y3.1873 I.4641 J.9081
N5510 X1.6485 Y3.1979 I.4667 J.8675
N5520 X1.6303 Y3.2085 I.4499 J.7934
N5530 X1.6119 Y3.2198 I.4484 J.7499
N5540 X1.5946 Y3.231 I.423 J.6694
N5550 X1.5768 Y3.2433 I.416 J.6218
N5560 X1.5607 Y3.2552 I.3781 J.5313
N5570 X1.5365 Y3.2746 I.3623 J.4773
N5580 X1.5034 Y3.3059 I.2569 J.3044
N5590 G1 X1.298 Y3.5694
N5600 G3 X.9332 Y3.7476 I-.3648 J-.2843
N5610 X.7334 Y3.7022 J-.4625
N5620 X.4707 Y3.2851 I.1998 J-.4171
N5630 X.4824 Y3.1817 I.4625
N5640 G1 X.5572 Y2.856
N5650 G2 X.5606 Y2.8106 I-.3949 J-.0525
N5660 X.5607 Y2.7999 I-.5992 J-.0107
N5670 X.5604 Y2.7796 I-.5993
N5680 X.5594 Y2.7595 I-.6517 J.0221
N5690 X.5577 Y2.7381 I-.7466 J.0484
N5700 X.5555 Y2.7176 I-.7884 J.0739
N5710 X.5526 Y2.6961 I-.8675 J.1041
N5720 X.5494 Y2.6753 I-.9026 J.1312
N5730 X.5455 Y2.6537 I-.9713 J.1641
N5740 X.5412 Y2.6327 I-1.0015 J.1923
N5750 X.5364 Y2.6111 I-1.0625 J.2272
N5760 X.5312 Y2.5899 I-1.0889 J.2562
N5770 X.5254 Y2.5682 I-1.1438 J.2927
N5780 X.5193 Y2.5468 I-1.1669 J.3224
N5790 X.5126 Y2.5251 I-1.2168 J.3604
N5800 X.5056 Y2.5037 I-1.2371 J.3907
N5810 X.4981 Y2.4819 I-1.2827 J.4297
N5820 X.4903 Y2.4603 I-1.3007 J.4605
N5830 X.482 Y2.4385 I-1.3425 J.5006
N5840 X.4733 Y2.4169 I-1.3584 J.5318
N5850 X.4642 Y2.3951 I-1.3968 J.5728
N5860 X.4547 Y2.3735 I-1.4106 J.6044
N5870 X.4448 Y2.3517 I-1.446 J.646
N5880 X.4345 Y2.33 I-1.458 J.678
N5890 X.4238 Y2.3082 I-1.4906 J.7204
N5900 X.4127 Y2.2866 I-1.5008 J.7527
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N5910 X.4012 Y2.2648 I-1.5308 J.7957
N5920 X.3894 Y2.2432 I-1.5394 J.8283
N5930 X.3771 Y2.2215 I-1.567 J.8718
N5940 X.3645 Y2.2 I-1.574 J.9046
N5950 X.3515 Y2.1783 I-1.5992 J.9486
N5960 X.3382 Y2.1568 I-1.6048 J.9816
N5970 X.3244 Y2.1353 I-1.6279 J1.0261
N5980 X.3103 Y2.1139 I-1.632 J1.0592
N5990 X.2957 Y2.0924 I-1.653 J1.104
N6000 X.2809 Y2.0711 I-1.6556 J1.1373
N6010 X.2656 Y2.0498 I-1.6746 J1.1825
N6020 X.25 Y2.0286 I-1.676 J1.2159
N6030 X.234 Y2.0074 I-1.693 J1.2614
N6040 X.016 Y2. I-.218 J3.2068
N6050 G1 X0.
N6060 G40 Y0.
N6070 M50
N6080 M30
%
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Appendix C. CAD model for gear part sample