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MACHINING STABILITY OF WIRE EDM OF TITANIUM

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by

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Machining Stability of Wire EDM of Titanium

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This paper presents an experimental investigation of wire electro-discharge machining (WEDM) of titanium alloy. The outstanding characteristics of titanium alloys such as their compatibility and noticeable physical, mechanical and biological performances has led to increased application of them in various industries especially in biomedical industries over the last 50 years. However, due to low thermal conductivity of titanium and its alloys and their reactivity with cobalt in most tool materials, there are some difficulties in machining titanium and its alloys by conventional machining. On the other hand, unconventional machining processes especially Wire Electrical Discharge Machining (WEDM) are more appropriate techniques for machining difficult –to-machine materials like titanium and its alloys. Electrically conductive materials are cut by Wire EDM that uses a wire as electrode in an electro-thermal mechanism. Since there is no direct contact between wire electrode and the work pieces in WEDM methodology, the mechanical stress and vibration problems in machining are eliminated. The focus of this thesis is on machining of titanium with WEDM because of the above-mentioned features of WEDM and its suitability for machining titanium and its alloys.

A brief review of existing studies on WEDM of titanium alloy is included in this study to clarify the motivation of conducting this research. In this study the effect of seven process parameters including voltage, pulse width, time between two pulses, servo reference voltage, pulse current, injection pressure and wire tension on process performance parameters such as cutting speed, wire rupture and surface integrity are investigated. All experiments are conducted using Charmilles WEDM. A Taguchi L18 design of experiment (DOE) is applied to determine the effect of significant parameters on WEDM performance. In addition, this study analyzes the effect of two wire types, zinc-coated brass wire and high-speed brass wire, on machining performance. Several experiments are done in order to find the effect of machining parameters and their setting on wire breakage. In order to analyze the effect of wire type on surface characteristics, Scanning Electron Microscopic (SEM) examination of machined surfaces is performed. This thesis applies Data Dependent System approach (DDS) to analyze the surface profile of titanium work pieces that are machined by both wire types.

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Chapter 1

Introduction and Problem Description

1.1 Introduction

Non-traditional machining processes are called advanced manufacturing processes since they are established in modern industries. These machining processes utilize various energies such as mechanical, thermal, electrical or chemical or combinations of these energies to remove extra material. In addition, non-traditional machining processes do not use sharp cutting tools.

Traditional machining processes such as turning, drilling, shaping and milling are not proper techniques to machine extremely hard and brittle materials. Traditional machining processes may have many difficulties in machining such materials. In machining extremely hard and brittle materials, conventional processes may not be feasible, satisfactory or economical due to the following characteristics:

- The tool is harder than work piece.
- There is a direct mechanical contact between the tool and the work piece.
- It is difficult to machine complicated shapes and obtain close tolerances.

Thus, non-conventional processes are applied instead of conventional methods for extremely hard and brittle materials.

Non-traditional manufacturing processes are classified by distinct machining mechanisms, machining system components and technological characteristics.

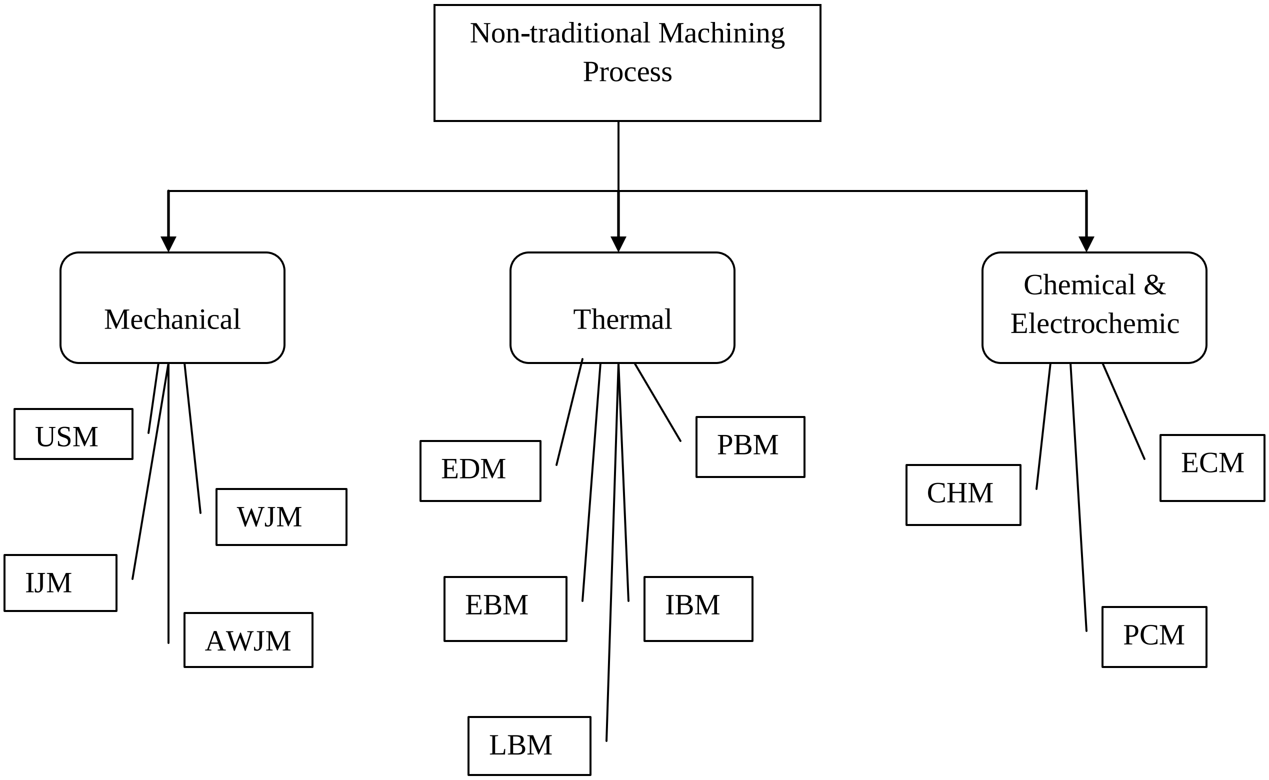


Figure 1.1 Classification of Non-traditional Process

1.2 Electrical Discharge Machining (EDM)

The effect of electrical discharge on material erosion was studied by Joseph Priestily in 1770 but was not used in machining of metals until 1930. Two Russian scientists, B. R. Lazarenko and N. I. Lazarenko, invented the Electrical Discharge Machining (EDM) process in 1943 [1].

Among non-traditional machining processes, EDM is applied widely rather than other methods. EDM utilizes a thermo electrical process in which material is removed from work piece by applying heat energy of sparks. Electrical discharge is repeated between two electrodes (tool and work piece) in the presence of a dielectric fluid. The temperature of the area under spark increases. As a result, the materials melt and vaporize from localized area by using spark energy [2,3,4,5].

Electrical conductive materials can be machined by EDM process. The EDM process is able to machine hard, difficult-to-machine materials. Parts with complex, precise and irregular shapes for forging, press tools, extrusion dies, difficult internal shapes for aerospace and medical applications can be made by EDM process.

There are several EDM processes that are shown in the Figure 1.2. This classification of EDM into three main categories is introduced by Pandey and Shan [6].

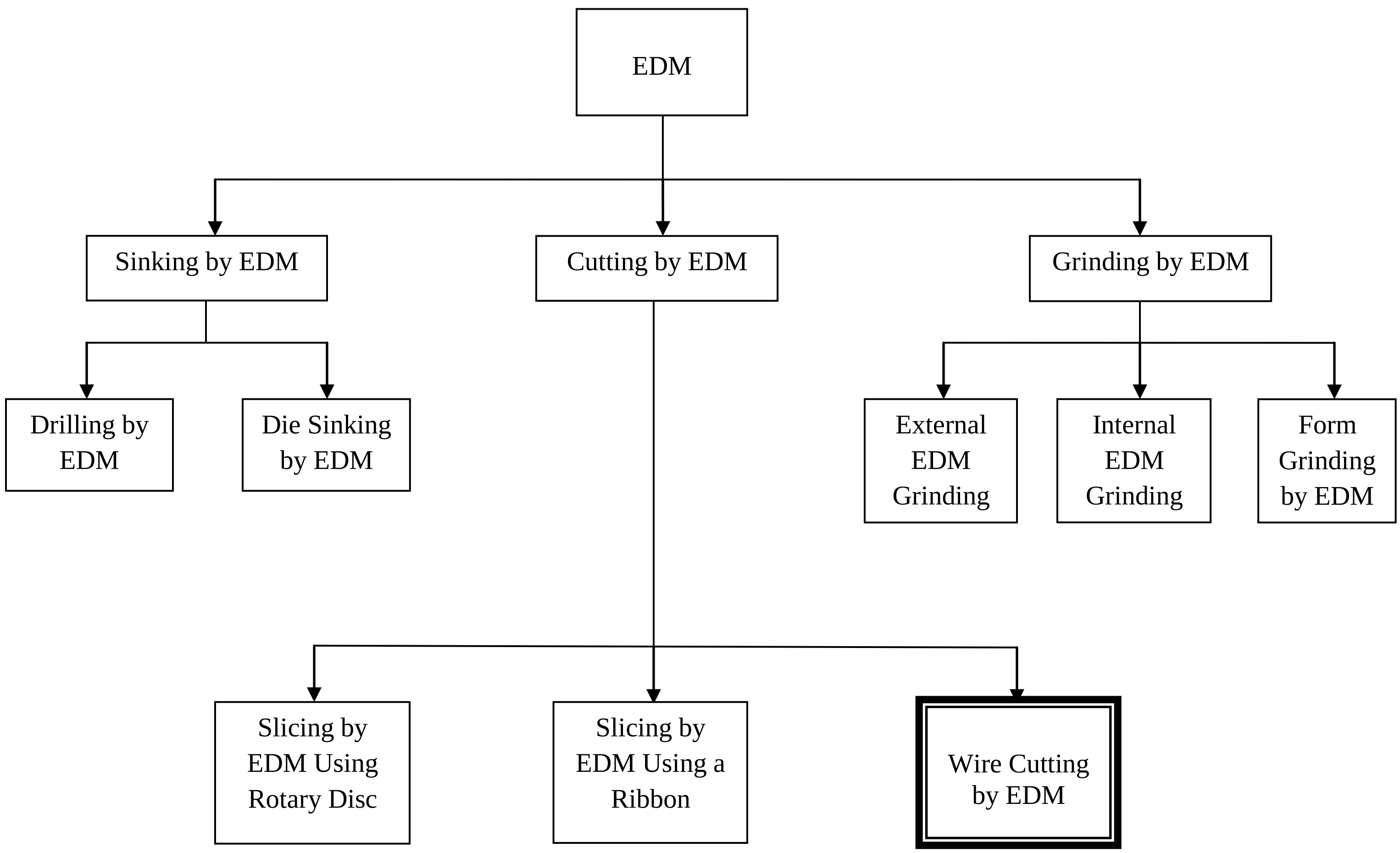


Figure 1.2 Classification of EDM

1.3 Wire Electrical Discharge Machining (WEDM)

The world's first WEDM was produced by the SWISS FIRM 'AGIE' in 1969. The first WEDM machine worked simply without any complication and wire choices were limited to copper and brass only. Several researches were done on early WEDM to modify its cutting speed and overall capabilities. In recent decades, many attempts were done on Wire EDM technology in order to satisfy various manufacturing requirements, especially in the precision mold and die industry. Wire EDM efficiency and productivity have been improved through progress in different aspects of WEDM such as quality, accuracy, precision and operation [7].

A schematic of a WEDM process is shown in Figure 1.3, where the wire and the work piece are immersed in a dielectric fluid.

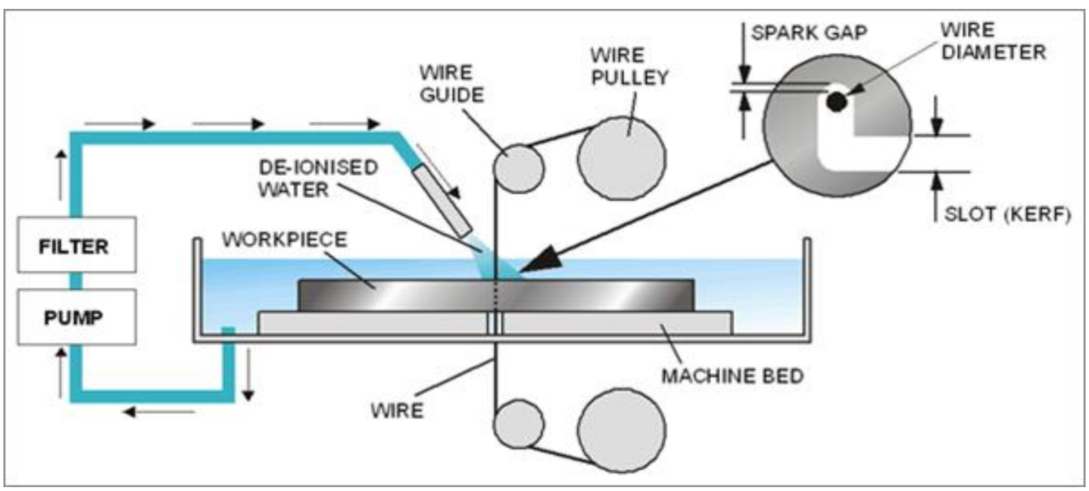


Figure 1.3 Schematic Diagram of WEDM System

Wire EDM uses electro-thermal mechanisms to cut electrically conductive materials. The material removal mechanism in WEDM is based on the melting and vaporization of material. The applied voltage creates a channel of plasma in the working gap between work piece and wire that are immersed in de-ionized water. There is a small gap between wire and work pieces that the discharge takes place with heavy flow of current in it. The area where discharge takes place is heated to extremely high temperature that leads to melting and removing of surface material. The removed particles are flushed away by the flowing dielectric fluid.

1.3.1 Application of Wire EDM Process

Wire EDM process can be applied in various industries such as aerospace, automotive, furniture, medical, jeweler industry and renewable energy. Also, WEDM process is one of the best choices for producing tall parts, long tubes, large heavy gears and cavities in one side of tube. Unattended operation for hours or even days is a capability for the Wire EDM machine.

1.3.2 Advantages of Wire EDM Process

- Mechanical stress is eliminated during machining since there is not any contact between wire and work piece.
- This process is able to produce complicated work pieces in different shapes and size.
- WEDM process can be applied for repairing damaged parts.
- Any electrical conducting materials can be machined by WEDM process apart from its hardness, toughness and brittleness.

1.3.3 Disadvantages of Wire EDM Process

- High cost is required for wire and machining.
- There is a problem regarding the formation of recast layer on machined part surface.
- WEDM process shows very slow cutting rate.
- WEDM process is not applicable for machining very large work piece.

1.4 Purpose of the Research

The outstanding properties of titanium such as high strength, high strength to weight ratio, high toughness, corrosion resistance and long standing are the main cause of widely use of titanium and its alloys. Machining of titanium in the minimum time and with maximum precisian is a considerable issue in all application fields of titanium such as biomedical applications, automobile, aerospace, chemical field, electronic, gas, food and especially biomedical industries. Over the past three decades, application of titanium in medical and biomedical devices has expanded due to development of new processing methods such as computer-aided machining and Wire Electrical Discharge Machining (WEDM). WEDM process is a non-traditional machining method that has provided an effective solution to machine difficult-to-machine materials.

The quality of engineering parts and components is measured by surface roughness that is one of the machining factors. The huge heat generated during WEDM leads to the microstructure and material composition change and a layer of oxide produced on the machined material surface. Therefore, machining titanium with a high quality, smooth surface and high accuracy is a purpose for most of the industries and researchers. Numerous studies have been done on improving surface roughness and different methods were applied such as Data-Dependent System (DDS) that is used in this study.

In addition, cutting speed is another performance requirement that wire electrical discharge machine should satisfy it. Producing more work in less time is important for many industries and researches. On the other hand, WEDM process exhibits very slow cutting speed. Therefore, improving WEDM cutting speed (or MRR) and WEDM productivity is researcher’s purpose.

The temperature increases during machining of titanium because of low thermal conductivity and high chemical reactivity of titanium. Thus, the probability of wire breakage increases during machining of titanium when the cutting temperature at wire/work piece enhances. The wire breakage during machining materials has an important and direct effect on WEDM process performance such as cutting speed and surface roughness. Applying different wire electrode materials and types is one of the solutions for performance improvement issue. Each type of wire materials leaves a distinct impression on WEDM process responses. Also, different wire types affect differently on various work piece materials. Based on the researchers investigation the wire is used in WEDM need to provide some requirements such as high electrical conductivity, sufficient tensile strength at high temperatures, low melting temperature and high heat conductivity in order to reach to high performance. As a result, identification of the most proper wire electrode for machining of titanium with high performance and productivity plays an important role for WEDM process.

The first objective was trying different wire electrode materials in WEDM of titanium and finding their effects on responses such as cutting speed, surface roughness and wire breakage since wire electrode plays an important role in improvement of WEDM performance.

The second objective was applying stochastic models and analysis techniques in order to study surface roughness profiles by Data Dependent System (DDS).

On the other hand, WEDM performance includes Material Removal Rate (MRR), wire rupture and surface finish of machined materials that can be influenced by process parameters. Some of process parameters have significantly influence on the WEDM performance and others have insignificant effect. In addition, the effect of process parameters can be changed by electrode and work piece materials and machining conditions. Optimization of WEDM process, finding optimal values of process parameters and determination of a proper combination of process inputs are objectives of this study.

The third objective was optimization of machining parameters during machining of titanium for both wire materials by utilizing Taguchi method.

1.5 Organization of Thesis

- Chapter 1 covers brief introduction to non-traditional machining, Electrical Discharge Machining (EDM), Wire Electrical Discharge Machining (WEDM), WEDM principal, advantages, disadvantages and applications. The objectives of the investigation are also described.
- Chapter 2 presents the literature review of EDM and WEDM process. The available literature of EDM is written briefly. On the other hand, a detailed WEDM literature review is available that is categorized in two classifications, *i.e.* literature based on WEDM of titanium and WEDM optimization. The gap of literature is also discussed.
- Chapter 3 presents the area of research work and situation that experiments have been done under them. Also, the electrical parameters of process were described.
- Chapter 4 covers introduction and description of adopted methodology, Taguchi design. This chapter includes a presentation of Toughie's philosophy, experimental design strategy and data collection and analysis.
- Chapter 5 presents the analysis and results of the response variables. Analysis of Variance (ANOVA), main effect plots and optimal design conditions are obtained for each type of wire and work piece materials. In addition, SEM micrographs have been drawn to analysis of machine material surface.
- Chapter 6 covers a brief literature review about wire materials and types that are applied in WEDM process. Also, the effects of two different wire types on response variables especially wire rupture is discussed.

- Chapter 7 presents the modeling of surface profiles of machined work piece by WEDM process by applying Data Dependent System (DDS).
- Chapter 8 presents the conclusion and recommendation from the experimental works.

Chapter 2

Literature Review

2.1 Introduction

Titanium is a metal with excellent corrosion resistance, fatigue resistance, a high strength-to-weight ratio that is maintained at elevated temperature. Titanium and its alloys are attractive and important materials in modern industry due to their above-mentioned unique properties [9,10].Titanium is a very strong and light metal which is 45% lighter than steel and only 60% heavier than aluminum. It is stronger than aluminum but as strong as steel. This property causes that titanium has the highest strength-to-weight ratio in comparison with the other metal that are studied to medical use. Titanium is also incredibly durable and long-lasting. When titanium cages, rods, plates and pins are inserted into the body, they can last for more than20 years. Titanium's non-ferromagnetic property is another benefit, which allows patients with titanium implants to be safely examined with MRIs and NMRIs [11, 12, 13].

This outstanding properties are the main cause of widely use of titanium and its alloys. Titanium and its alloys are used in many industries such as biomedical applications, automobile, aerospace, chemical field, electronic, gas and food industry [14].In recent decades, titanium is applied widely in biomedical and medical field because it is absolutely proper join with bone and other body tissue, immune from corrosion, strong, flexible and compatible with bone growth. Titanium is used in different medical specifications such as dental implants, hip and knee replacement surgeries, external prostheses and surgical instruments [12,15,16]. On the other hand, there is some limitation for titanium use because of its initial high cost, availability and manufacturability. Titanium is more expensive than other materials because extraction process and melting of titanium is very complex and difficult. Also, inherent properties of titanium lead to poor machinability of titanium [17].

Machining titanium and its alloy by conventional machining methods has some difficulties such as high cutting temperature and high tool wear ratio. Thus, titanium and its alloys are classified as “difficult-to-machine” materials. The low thermal conductivity and reactivity with cobalt in most tool materials result in work hardening and poor process performance. Therefore, unconventional machining processes are introduced for machining titanium and its alloys [10,13, 14].

2.2 Literature Review

Research and development on titanium’s medical application is concentrated on studying titanium properties in order to enhance its mechanical properties, prevent corrosion and surface treatment that improve biocompatibility.

All research and development about the titanium properties as biomedical and health care application in detail were reviewed [18]. The appropriate microstructure of titanium with optimum mechanical properties such as wear resistance and mechanical and biological compatibility was discussed. Also, various surface modification techniques were discussed in their paper [19]. The corrosion and fatigue behavior of titanium that were used in implant considering the effect of different environmental condition were reviewed [20, 21].

Electrical Discharge Machining (EDM) and Wire Electrical Discharge Machining (WEDM) can be considered as non-traditional machining methods that have some advantages for machining of titanium and its alloys. There is not a mechanical contact between tool and work piece in non-traditional process and EDM and WEDM remove work material by thermal erosion. Non-traditional machining processes use a tool material softer than work piece materials that provide a solution to produce complicated shapes of titanium. Also, WEDM and EDM have many applications and potential among other electro-thermal processes in field of conductive materials. Thus, difficult-to-machine materials like titanium can be machined by non-conventional methods easier [22].

The effect of different conditions and electrode materials on machining of titanium by EDM was investigated. They considered material removal rate (MRR) and surface finish as machining characteristics [23]. The effect of input parameters on surface roughness in EDM process of titanium was studied. They developed a mathematical method for correlating influence of input parameters on surface finish of work piece [24]. The influence of different electrode profiles on responses in EDM of titanium was tested. They considered the effect of various electrode profiles such as size and shape on surface roughness and MRR of titanium that is machined by EDM [25]. The influence of the effect of electrode cooling on the elements migration between electrodes during EDM of titanium alloys was studied. They concluded electrode cooling by liquid nitrogen during EDM can reduce surface contamination between electrodes [26]. Liquid Nitrogen at 195°C as a new coolant into the electrode among the EDM process was presented. The effect of new coolant on MRR, surface roughness and electrode wear the EDM process of titanium has been studied [27]. Optimization of machining parameters during EDM process of titanium was worked. They used Taguchi method and grey relational analysis to evaluate parameters effect on performance characteristics [28]. An artificial neural network (ANN) model was developed to predict the behavior of input variables during EDM process of titanium. It was found that peak current has the highest influence on MRR, surface roughness and tool wear ratio.

Also, the levels of input parameters for optimizing machining performance are achieved based on this model [11]. Experiments on a die-sinking EDM were performed with two different electrode types, bundled electrode and a solid electrode for cutting titanium. Results proved that applying bundled electrode leads to higher performance and lower tool wear ratio [14].

Wire Electrical Discharge Machining (WEDM) is a special form of EDM that uses small diameter wire as electrode to cut the work piece. Wire EDM uses electro-thermal mechanisms to cut electrically conductive materials. In this study WEDM seems to be a better choice for machining of titanium and its alloys because it has an extreme potential to address the problems of machining titanium. Several researchers have attempted to improve the performance characteristics of WEDM of titanium in different aspects of the process.

A new methodology was employed to find the influences of process parameters on characteristics of titanium surface machined by WEDM process. Also, Taguchi and analysis of variance were used to analysis the effect of machining parameters on surface based on the metallurgical changes. They repeated all experiments with two different wire types. Coated wire produces uniform surface in comparison with uncoated wire [10]. A strategy and advanced optimization were proposed to determine the optimal combination of control parameters of WEDM for obtaining higher cutting efficiency and accuracy while machining titanium aluminide alloy by Artificial Neural Network (ANN). ANN was able to predict the performance of all process parameters combinations. Then, the set of all optimum parametric combination were identified between all predictions by multi-objective optimization strategy. In addition, a computer program was developed to search optimal parameters combination based on multi-objective optimization strategy [29]. Several experiments with two different work piece materials, titanium and cemented carbide, in WEDM process were performed. Three various wire types, uncoated wire, zinc coated wire and brass coated wire, were applied to machine the work pieces in order to achieve higher efficiency of cutting. They developed a semi-empirical model based on the properties of machined materials and WEDM parameters to find their influence on the volumetric efficiency of cutting [30]. The Taguchi methodology involving eight control factors with three levels for an orthogonal array L27 (3^8) was used to determine the optimal parameters for surface finish in WEDM of titanium alloys. In addition, they optimized developed surface roughness model by Genetic Algorithm (GA) in order to obtain optimal control parameters [22]. The influence of WEDM on the corrosion rate and depth of damaged layer in the surface of pure titanium grade 4 and Ti-6Al-4V (grade 5) was investigated. The depth of damaged layer and corrosion rate were measured by SEM/EDS examination. These examinations were performed after cutting parts by WEDM process. Also, Taguchi design was used for analysis of the process parameters on the depth of damaged layer [31]. The effect of machining parameters on surface roughness of alpha-beta titanium work pieces that machined by wet and dry WEDM was reported. Investigation of work pieces surface indicated wet WEDM gives better surface roughness compared to dry WEDM. Also, wet WEDM is able to improve surface roughness of titanium work pieces [32]. K.P. Rajurkar and Lin Gu reviewed recent research about machining of titanium and its alloys by EDM and Wire EDM. It reported on the influence of tool, dielectric liquid and different machining parameters on the machining criteria such as surface roughness, material removal rate and tool wear ratio. [17,33] conducted experiments on WEDM for titanium and its alloys. The experiments were performed in order to determine how the process parameters change the machining performance such as surface roughness, cutting rate and gap current. Moreover, they studied the relation between WEDM parameters and wire breakage.

These studies were performed to enhance the WEDM of titanium performance and to solve the machining of titanium problems.

Wire electrode size, shape and material play important role in achieving improvement in WEDM performance and prevention of wire breakage. Thus, many researchers studied wire electrode characteristics and experimented different materials and methods.

A thermal model was developed in order to investigate the influence of physical process parameters on wire rupture. The temperature rise in wire electrode can be calculated with this model to determine the effect of process conditions [34]. A WEDM sparking frequency monitoring system was introduced in order to predict the wire breakage in WEDM process. The wire rupture prediction can be achieved by collecting the data of sparking frequency in the wire breakage process [35]. The influence of the wire material properties on WEDM machinability was reported. Also, they determined the relation between physical properties of wire materials and WEDM performance [36]. The wire failure in WEDM process was investigated. They applied SEM photographs and Artificial Neural Network (ANN) to analysis the effect of various wire materials and process conditions on WEDM process performance [37]. Two new wires that are called High-Falcon (HIF) and High-Eagle (HIE) were introduced and their properties and difference were analyzed. They developed HIF electrode to achieve high-speed and accurate cutting, and the HIE electrode for super-high-speed cutting [38]. The development of new wire was studied that is called composite wires. The purpose was to produce a wire with a high strength core, good conductivity and good sparking ability in order to achieve high precision cutting [39]. The recent development in wire electrode types and their characteristics during WEDM process was reviewed. In their study different wire types such as plain wire, wire with different coated and core materials were compared to find which one gains high performance

WEDM [40]. The wire breakage reasons and its effect on machining performance in WEDM process were identified and explained. Also, they developed a new system that can help operator to identify the work piece with varying thickness. The identification of the varying thickness of work piece before process is crucial since it is one of the wire rupture reasons in WEDM process [41]. The effect of coated wire on productivity and surface integrity of machined materials by WEDM were evaluated. They focused on aerospace materials such as Ti-6Al-2Sn-4Zr-6Mo, and Udimet 720 nickel based super alloy solution treated and aged to ~HV490 [42].

WEDM optimization is a research area that many researchers performed enormous probes with different methods and situations.

The Taguchi method was applied in order to determine the effect of WEDM process parameters on process responses such as Material Removal Rate (MRR), surface roughness and width of cut. The electrical parameters that were considered in their research include wire speed, wire tension, pulse frequency, dielectric flow rate, discharge current and pulse duration. They performed experiments with steel material and different level of parameters. Also, the optimal value of significant parameters that maximize MRR, minimize SR and width of cut were specified [43,44,45,46,47]. [48,49,50,51] concentrated on improving surface integrity of materials machined by WEDM process. They studied the relation between process parameters and surface roughness. Various methods such as SEM photographs, EDS graphs and ANOVA tables were utilized to analyze surface characteristics. The best control setting of WEDM was selected by applying formulation and solution of a multi-objective optimization problem. Also, two methods, one based on explicit enumeration and the other using dynamic programming were employed in order to obtain the non-dominated points [52]. The effect of electrical conductivity of dielectric fluid on WEDM process performance was investigated. The dielectric plays two crucial roles in WEDM process. It washes away debris from gap and is used as a coolant after the spark [53]. FEM simulation model was used to analyze the machined surface temperature. In fact, they determine the effect of cutting parameters on surface by measuring the depth of temperature from top surface [51]. The influence of the thickness of graphite work piece on process performance was studied. They developed a mathematical correlation to predict cutting time, accuracy and cost of machining of graphite work piece by WEDM process [54]. A new approach was presented in order to model and optimize the relation between input parameters and obtained responses. The new approach is Response Surface Modeling (RSM) that is a mathematical and statistical method [55]. A comprehensive investigation was performed to find the influence of WEDM input parameters on machining quality. He applied some methods such as Taguchi technique, RSM and multi response optimization to improve the quality characteristics of H-11 hot die steel machined [56].

2.3 Identified Gaps in the Literature

After a comprehensive review of literature in WEDM process of different materials and titanium area it is obvious that there are a number of gaps in machining of Titanium by WEDM.

- There is little research about wire rupture during WEDM of titanium. Moreover, the effect of process parameters on wire breakage has not been considered.
- Multi-response (MRR, SR and wire rupture) optimization of WEDM of titanium is another area which has not been paid attention in the past studies.
- Limited studies have been carried out on influence of coated and uncoated wire on process responses in WEDM of titanium.

Chapter 3

Experimental Situation and Process Parameters Selection

3.1 Machine

The Charmilles Model 2020 Wire EDM (WEDM) was used to carry out the experiments. The Charmilles Model 2020 (WEDM) allows operator to choose input parameters and change their values during machining.

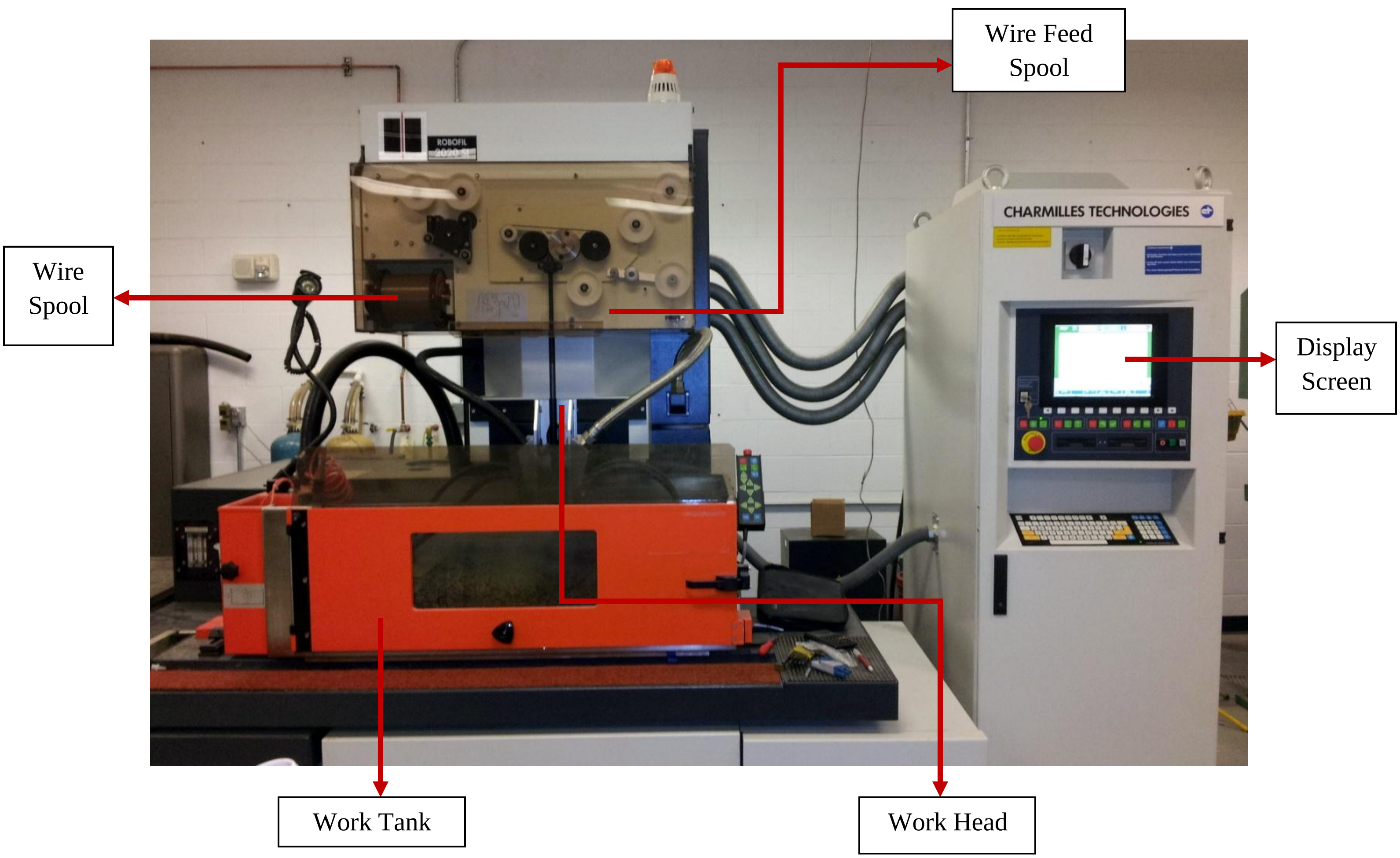


Figure 3.1 Pictorial View of WEDM

The wire EDM machine calculates the cutting speed, and the value is displayed on the output screen of the CNC interface. The machine consist of work table, work tank, rotary shaft, wire running system, dielectric supply system and microcomputer based control cabinet that are shown in Figure 3.1. Charmilles Model 2020 Wire EDM moves in three axes X, Y and Z. The maximum part size which can be produced is 900 mm X 500 mm X 250 mm. Also, Charmilles Model 2020 Wire EDM cannot machine the parts that are heavier than 500 kg.

3.2 Work piece Materials

The Ti6Al4V and D2 steel were used as work piece materials for the present experiments. Titanium is a metal with excellent corrosion resistance, fatigue resistance, a high strength-to-weight ratio that is maintained at elevated temperature. It is a very strong and light metal which is 45% lighter than steel and only 60% heavier than aluminum. It is stronger than aluminum and is as strong as steel. D2 steel is an air hardening, high-carbon, high-chromium tool steel. High wear and abrasion resistant are its two most important properties. The chemical composition of Ti6Al4V and D2 steel are given in Table 3.1.

Ti6Al4V	C	Fe	Al	O	N	V	H	Ti
	0-0.08	0.22	6.08	0-0.2	0.05	4.02	0-0.15	Balance
D2 steel	C	Si	Cr	Mo	Ni	V	Ma	
	0.015	0.003	0.12	0.008	0.003	0.009	0.005	

Table 3.1 Chemical Composition of Work Piece Materials

Titanium and its alloys are used in many different industries such as biomedical applications, automobile, aerospace, chemical field, electronic, gas and food industry. The applications of D2 steel are numerous and the material can be used in many environments, such as: blanking dies, punches, knives and shear blades, forming rolls and tools.

3.3 Electrodes

Two types of wire electrode material were used namely high-speed brass wire and zinc-coated brass wire. High-speed brass wire was developed by OKI Electric Cable with high tensile special composition in order to achieve higher quality and higher speed cutting in Wire EDM machine. Zinc-coated brass wire that was produced by OKI Electric Cable is a Hi-Tensile Zinc Coated Brass Wire. Putting zinc coating around brass wire enhances cutting speed, straightness and tensile strength which are key factors for the superior surface finishes. Table 3.2 illustrates the properties of wire electrodes.

Wire Name	**High-Speed Brass**	**Zinc-Coated Brass**
Material	High Purity Brass Special Composition	CuZnBrass,63/37CoreComposition with Zinc Coating
Tensile Strength	142,000 + PSI	130,000 PSI
Wire Diameter	0.25 mm	0.25 mm
Price	105$ (D-160)	117$ (D-160)

Table 3.2 Wire Electrodes Properties

3.4 Measurement of Process Output Responses

Cutting speed and surface roughness were considered as output responses of Wire EDM process and are presented in the following subsections.

3.4.1 Cutting Rate

For WEDM, large cutting rate is a desirable characteristic and high productivity of WEDM achieved with maximum amount of cutting speed. To measure the material removal rate, a straight cut is made into the work piece. When the wire had made approximately 50% of this cut, the steady cutting speed value was read off the graphical display. The S/N ratio and average value of the cutting speed for each variable at different levels were calculated from experimental data. Also, de-ionized water was selected as the dielectric for experiments, as that is the standard for Wire EDM.

3.4.2 Surface Roughness

One of a good predictor of Wire EDM performance is surface roughness because nucleation sites can be formed for cracks or corrosion by irregularity in the surface.

Roughness is a measure of the texture of a surface. It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if small, the surface is smooth. Roughness is typically considered to be the high frequency, short wavelength component of a measured surface.

In this study, Surfcom 130/480A was applied to measure the surface roughness of the cut samples that is shown in Figure 3.2. Surfcom 130/480A measures surface texture of metal and non-metal parts. Its small and compact size makes it easily transportable. The work piece is put under the horizontal stylus which traces the minute irregularities of the work piece surface. The horizontal stylus moves on the work piece surface and displacement during the trace. The roughness measurement and graph are digitally displayed on LCD display or can be printed.

Scanning Electron Microscopy (SEM) views of the WEDMed surfaces were taken by Quanta 200 FEG Scanning Electron Microscope. These photographs help us compare the effects of different wire types on machining of different work piece materials by analyzing surface integrity and characteristics.

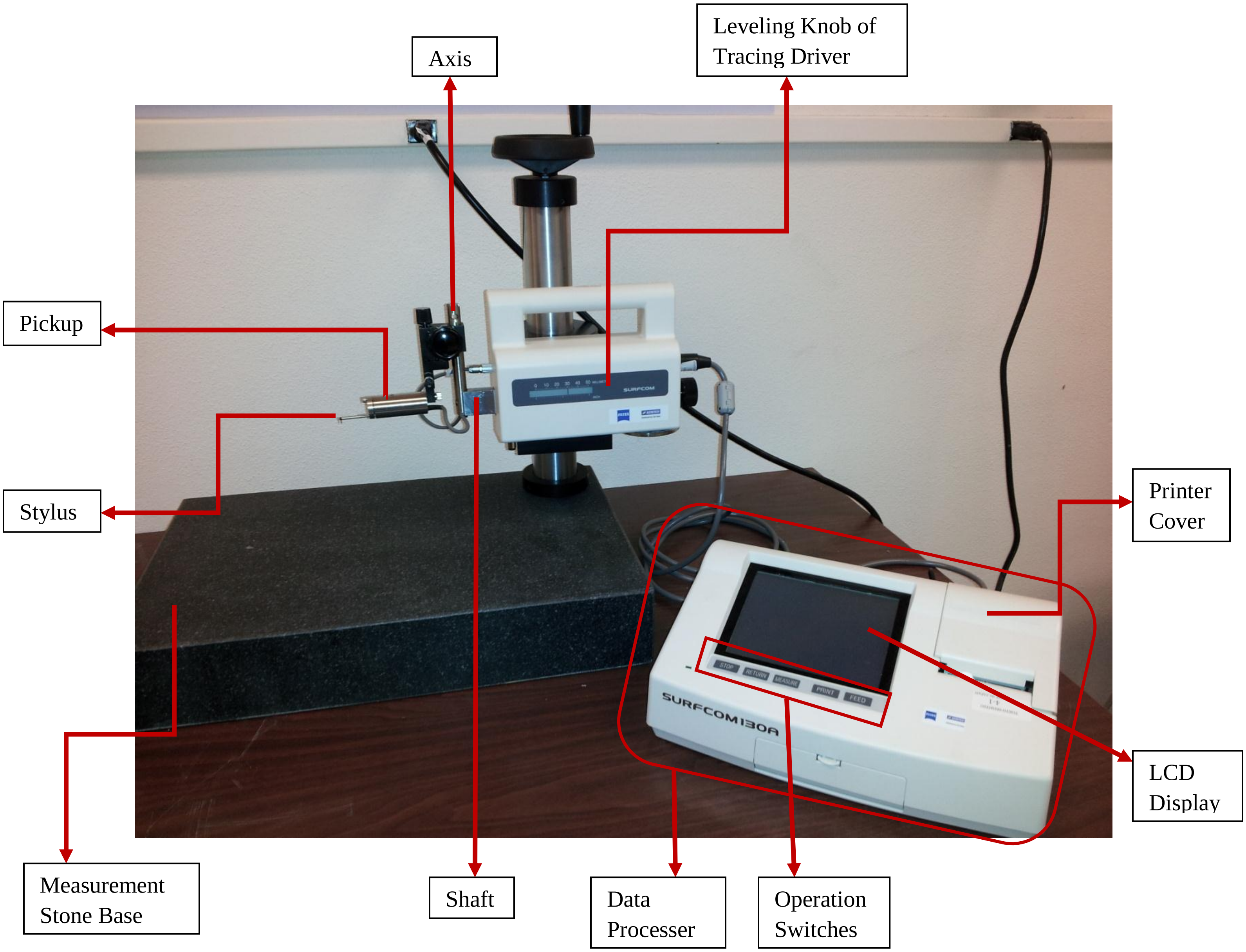


Figure 3.2 Pictorial View of Surfcom 130/480A

3.5 Selection of Process Parameter

An Ishikawa cause and effect diagram was constructed and is shown in Figure 3.3 to identify the process parameters that may affect the machining characteristics of WEDM machined parts.

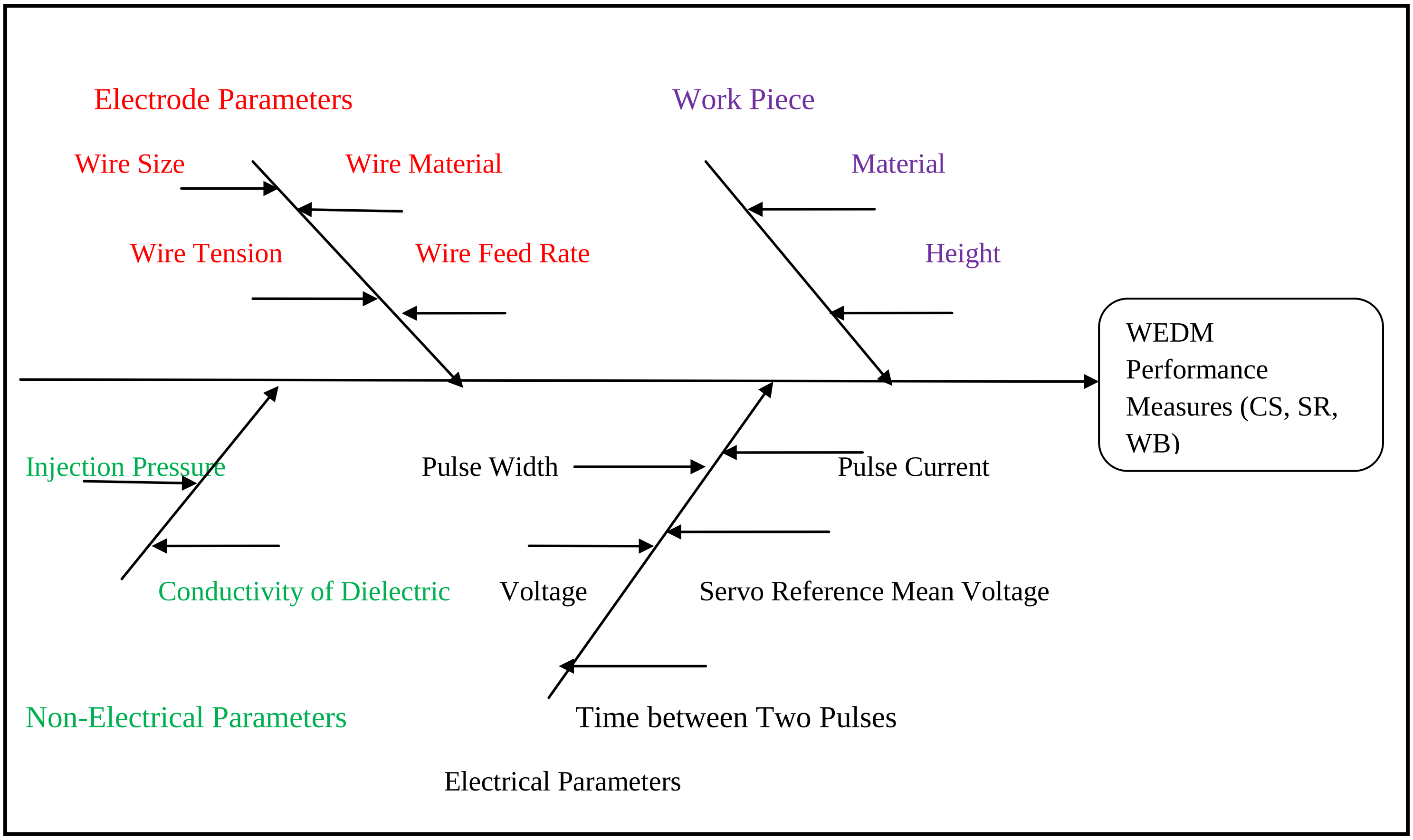


Figure 3.3 Ishikawa Cause and Effect Diagram for WEDM Process

The input process parameters and output characteristics are shown in Figure 3.3. They were selected from Ishikawa cause and effect diagram.

3.5.1 Pulse Width

The pulse width is referred as A and all the process is done during pulse duration (on time). During this time the voltage is applied across the electrodes, the current is generated and the work is accomplished [57]. The A setting time range available on the machine tool is 0.2-3.0 in steps of 0.2μs. Increasing pulse duration results in higher cutting speed because the single pulse discharge energy increases. Consequently, the broader and deeper craters will be produced that results in smoother surface. Also, higher pulse width leads to wire breakage [56,58,59].

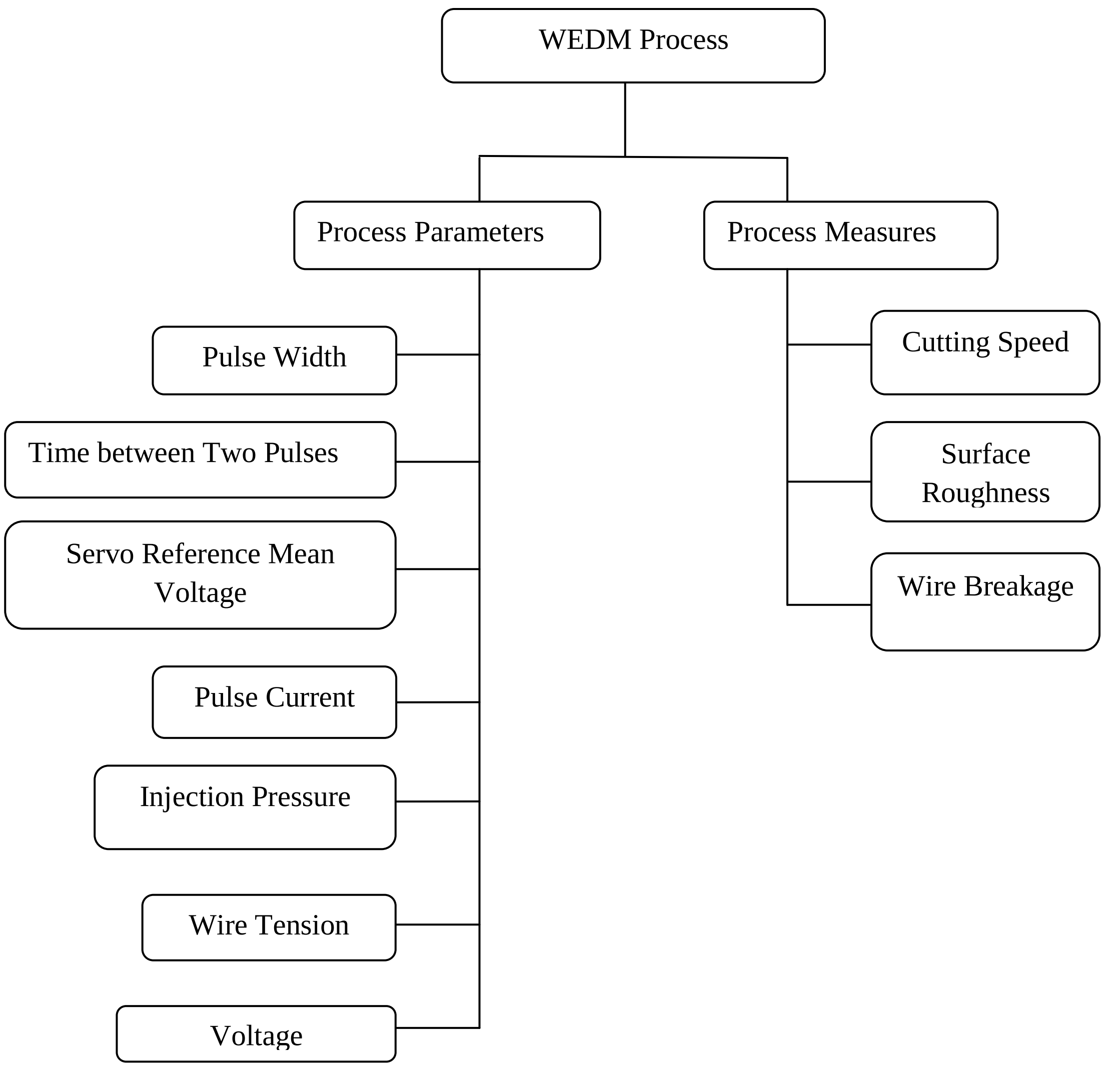


Figure 3.4 Process Parameters and Performance Measures of WEDM

3.5.2Time between Two Pulses

Time between two pulses is referred as B. In time between two pulses, the pulse rests and re-ionization of the dielectric take place since the machining take places during one pulse width [60]. The voltage is absent during this part of the cycle. The time between two pulses (B) setting time range available on the machine tool is 1.6-25μs.The sparking efficiency increases with a lower value of B due to more number of discharges in a given time. As a result, the cutting rate also increases. Too short time between two pulses leads to wire breakage and surface roughness will increases [59,61].

3.5.3Servo Reference Mean Voltage

The servo reference mean voltage is represented by Aj. The width of the gap between wire electrode and work piece is determined by servo voltage. The gape size increases with a high voltage setting that increases flushing and machining. Aj voltage range available on the present machine is 1-200V [3,62].

3.5.4Striking Pulse Current

The pulse current is represented by IAL. Pulse current is also another crucial primary input of WEDM process. The pulse current (IAL) setting current range available on the present WEDM machine is 2–33 ampere. The cutting rate and surface roughness will increase with the stronger discharge current [4].

3.5.5Injection Pressure

Injection pressure is for selection of flushing input pressure of the dielectric. The flushing pressure range on this machine is 0 to 16-20bars.Dielectric fluid rushes into the work piece to cool the area and remove eroded material. Input pressure of de-ionized water has a direct relation with the work piece thickness [2].

3.5.6Wire Tension

Wire tension determines the amount of stretch in wire between upper and lower wire guides. Higher wire tension is required for cutting work piece with more thickness. Low wire tension is used for cutting thin work pieces. Inaccuracy in job and wire breakage may happen because of improper setting of tension. The wire tension range available on the machine is 3-20daN.

Chapter 4

Experimental Design Methodology

A scientific approach to plan the experiments is a necessity for efficient conduct of experiments. By the statistical design of experiments the process of planning the experiment is carried out, so that appropriate data will be collected and analyzed by statistical methods resulting in valid and objective conclusions. When the problem involves data that are subjected to experimental error, statistical methodology is the only objective approach to analysis. Thus, there are two aspects of an experimental problem: the design of the experiments and the statistical analysis of the data. These two points are closely related since the method of analysis depends directly on the design of experiments employed. The advantages of design of experiments are as follows:

- Numbers of trials is significantly reduced.
- Important decision variables which control and improve the performance of the product or the process can be identified.
- Optimal setting of the parameters can be found out.
- Qualitative estimation of parameters can be made.
- Experimental error can be estimated.
- Inference regarding the effect of parameters on the characteristics of the process can be made.

In the present work, the Taguchi's method, and the response surface methodology have been used to plan the experiments and subsequent analysis of the data collected.

4.1 TaguchiExperimental Design and Analysis

4.1.1 Taguchi's Philosophy

Taguchi's comprehensive system of quality engineering is one of the greatest engineering achievements of the 20th century. His methods focus on the effective application of engineering strategies rather than advanced statistical techniques. It includes both upstream and shop-floor quality engineering. Upstream methods efficiently use small-scale experiments to reduce variability and remain cost-effective, and robust designs for large-scale production and market place. Shop-floor techniques provide cost-based, real time methods for monitoring and maintaining quality in production. The farther upstream a quality method is applied, the greater leverages it produces on the improvement, and the more it reduces the cost and time. Taguchi's philosophy is founded on the following three very simple and fundamental concepts (Ross, 1988; Roy, 1990):

- Quality should be designed into the product and not inspected into it.
- Quality is best achieved by minimizing the deviations from the target. The product or process should be so designed that it is immune to uncontrollable environmental variables.
- The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system-wide.

Taguchi proposes an “off-line” strategy for quality improvement as an alternative to an attempt to inspect quality into a product on the production line. He observes that poor quality cannot be improved by the process of inspection, screening and salvaging. No amount of inspection can put quality back into the product. Taguchi recommends a three-stage process: system design, parameter design and tolerance design (Ross, 1988, Roy, 1990). In the present work Taguchi’s parameter design approach is used to study the effect of process parameters on the various responses of the WEDM process.

4.1.2 Experimental Design Strategy

Taguchi recommends orthogonal array (OA) for lying out of experiments. These OA’s are generalized Graeco-Latin squares. To design an experiment is to select the most suitable OA and to assign the parameters and interactions of interest to the appropriate columns. The use of linear graphs and triangular tables suggested by Taguchi makes the assignment of parameters simple. The array forces all experimenters to design almost identical experiments (Roy, 1990).

In the Taguchi method the results of the experiments are analyzed to achieve one or more of the following objectives (Ross, 1988):

- To establish the best or the optimum condition for a product or process
- To estimate the contribution of individual parameters and interactions
- To estimate the response under the optimum condition

The optimum condition is identified by studying the main effects of each of the parameters. The main effects indicate the general trends of influence of each parameter. The knowledge of contribution of individual parameters is a key in deciding the nature of control to be established on a production process. The analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiments in determining the percent contribution of each parameter against a stated level of confidence. Study of ANOVA table for a given analysis helps to determine which of the parameters need control (Ross, 1988).

Taguchi suggests (Roy, 1990) two different routes to carry out the complete analysis. First, the standard approaches, where the results of a single run or the average of repetitive runs are processed through main effect and ANOVA analysis (Raw data analysis). The second approach which Taguchi strongly recommends for multiple runs is to use signal- to- noise ratio (S/N) for the same steps in the analysis. The S/N ratio is a concurrent quality metric linked to the loss function (Barker, 1990). By maximizing the S/N ratio, the loss associated can be minimized. The S/N ratio determines the most robust set of operating conditions from variation within the results. The S/N ratio is treated as a response (transform of raw data) of the experiment. Taguchi recommends (Ross, 1988) the use of outer OA to force the noise variation into the experiment i.e. the noise is intentionally introduced into experiment. However, processes are often times subject to many noise factors that in combination, strongly influence the variation of the response. For extremely "noisy" systems, it is not generally necessary to identify specific noise factors and to deliberately control them during experimentation. It is sufficient to generate repetitions at each experimental condition of the controllable parameters and analyze them using an appropriate S/N ratio (Byrne and Taguchi, 1987).

In the present investigation, the raw data analysis and S/N data analysis have been performed. The effects of the selected WEDM process parameters on the selected quality characteristics have been investigated through the plots of the main effects based on raw data. The optimum condition for each of the quality characteristics has been established through S/N data analysis aided by the raw data analysis. No outer array has been used and instead, experiments have been repeated three times at each experimental condition.

4.1.3 Loss Function

The heart of Taguchi method is his definition of the nebulous and elusive term "quality" as the characteristic that avoids loss to the society from the time the product is shipped (Braker, 1986). Loss is measured in terms of monetary units and is related to quantifiable product characteristic. Taguchi defines quality loss via his "loss function". He unites the financial loss with the functional specification through a quadratic relationship that comes from a Taylor series expansion. The quadratic function takes the form of a parabola. Taguchi defines the loss function as a quantity proportional to the deviation from the nominal quality characteristic (Roy, 1990). He has found the following quadratic form to be a useful workable function (Roy, 1990):

$$l(y) = k(y - m)^2 \qquad [4.1]$$

Where,

L = Loss in monetary units

m = value at which the characteristic should be set

y = actual value of the characteristic

k = constant depending on the magnitude of the characteristic and the monetary unit involved

The loss function represented in Eq 4.1 is graphically shown in Figures 4.1. The characteristics of the loss function are (Roy, 1990):

- The farther the product's characteristic varies from the target value, the greater is the loss. The loss must be zero when the quality characteristic of a product meets its target value.
- The loss is a continuous function and not a sudden step as in the case of traditional (goal post) approach (Figure 4.2). This consequence of the continuous loss function illustrates the point that merely making a product within the specification limits does not necessarily mean that product is of good quality.

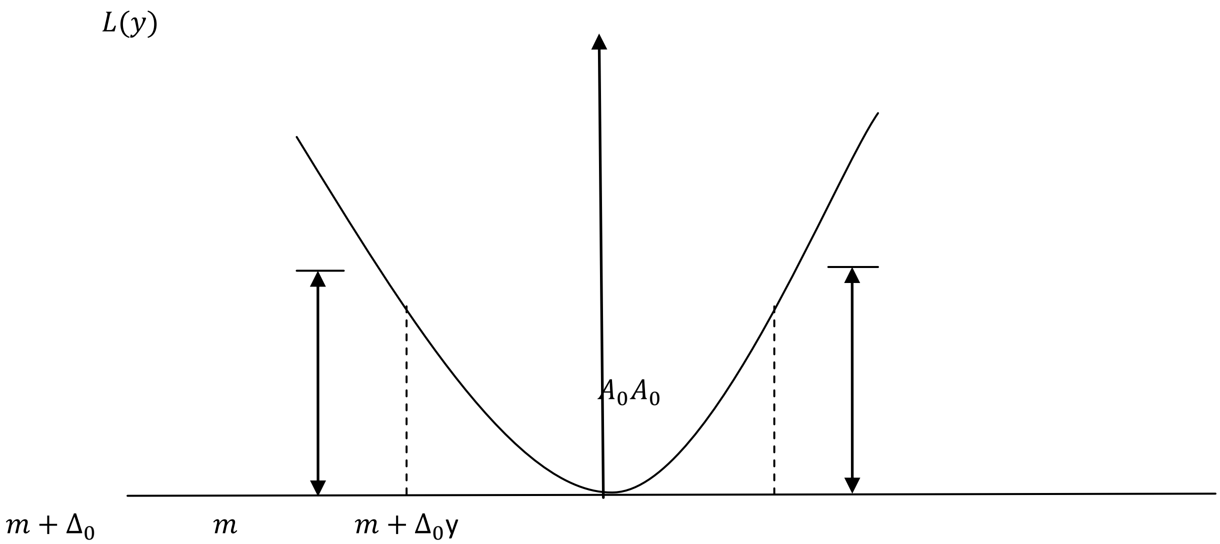


Figure 4.1 Taguchi Loss Function

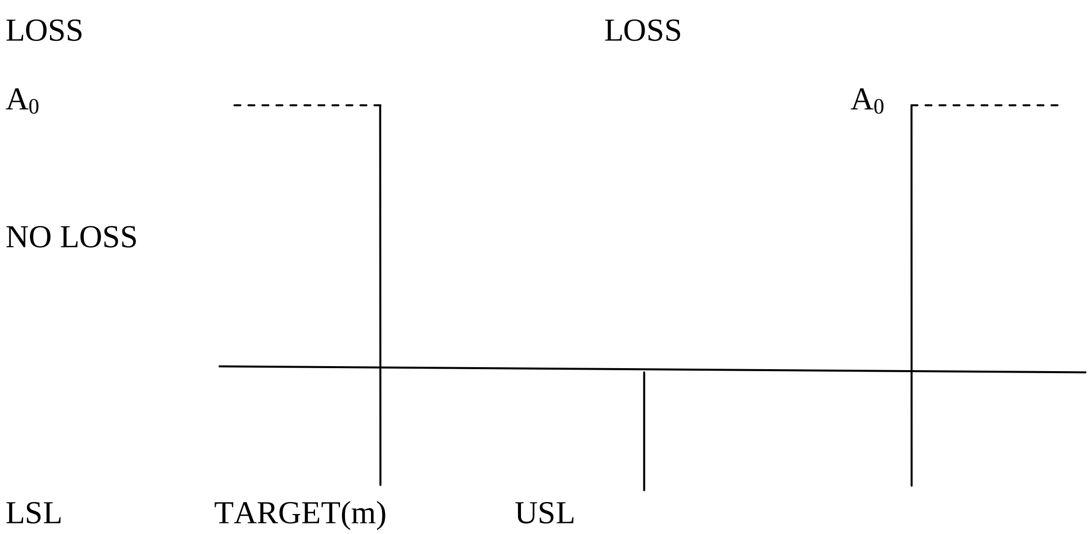


Figure 4.2 Traditional Approach

4.1.4 Signal to Noise Ratio

The loss-function discussed above is an effective figure of merit for making engineering design decisions. However, to establish an appropriate loss-function with its k value to use as a figure of merit is not always cost-effective and easy. Recognizing the dilemma, Taguchi created a transform function for the loss-function which is named as signal -to-noise (S/N) ratio (Barker, 1990).

The S/N ratio, as stated earlier, is a concurrent statistic. A concurrent statistic is able to look at two characteristics of a distribution and roll these characteristics into a single number or figure of merit. The S/N ratio combines both the parameters (the mean level of the quality characteristic and variance around this mean) into a single metric (Barker, 1990).

A high value of S/N implies that signal is much higher than the random effects of noise factors. Process operation consistent with highest S/N always yields optimum quality with minimum variation (Barker, 1990).

The S/N ratio consolidates several repetitions (at least two data points are required) into one value. The equation for calculating S/N ratios for “smaller is better” (LB), “larger is better” (HB) and “nominal is best” (NB) types of characteristics are as follows (Ross, 1988):

1. Larger the Better:

$$(S/N)_{HB} = -10 \mathrm{Log}(MSD_{HB}) \quad [4.2]$$

Where:

$MSD_{HB} = 1/R\sum_{j=1}^{R}(1/y_j^2)$

2. Small the Better:

$$(S/N)_{LB} = -10 \mathrm{Log}(MSD_{LB}) \quad [4.3]$$

Where:

$MSD_{LB} = 1/R\sum_{j=1}^{R}(y_j^2)$

3. Nominal the Best:

$(S/N)_{NB} = -10 \text{ Log } (MSD_{NB})$ [4.4]

Where:

$MSD_{NB} = 1/R\sum_{j=1}^{R}(y_j - y_0)^2$

R= Number of Repetitions

The mean squared deviation (MSD) is a statistical quantity that reflects the deviation from the target value. The expressions for MSD are different for different quality characteristics. For the “nominal is best” characteristic, the standard definition of MSD is used. For the other two characteristics the definition is slightly modified. For “smaller is better”, the unstated target value is zero. For “larger is better”, the inverse of each large value becomes a small value and again, the unstated target value is zero. Thus for all three expressions, the smallest magnitude of MSD is being sought.

4.1.5 Steps in Experimental Design and Analysis

The Taguchi experimental design and analysis flow diagram is shown in Figure 4.3The important steps are discussed in the subsequent article.

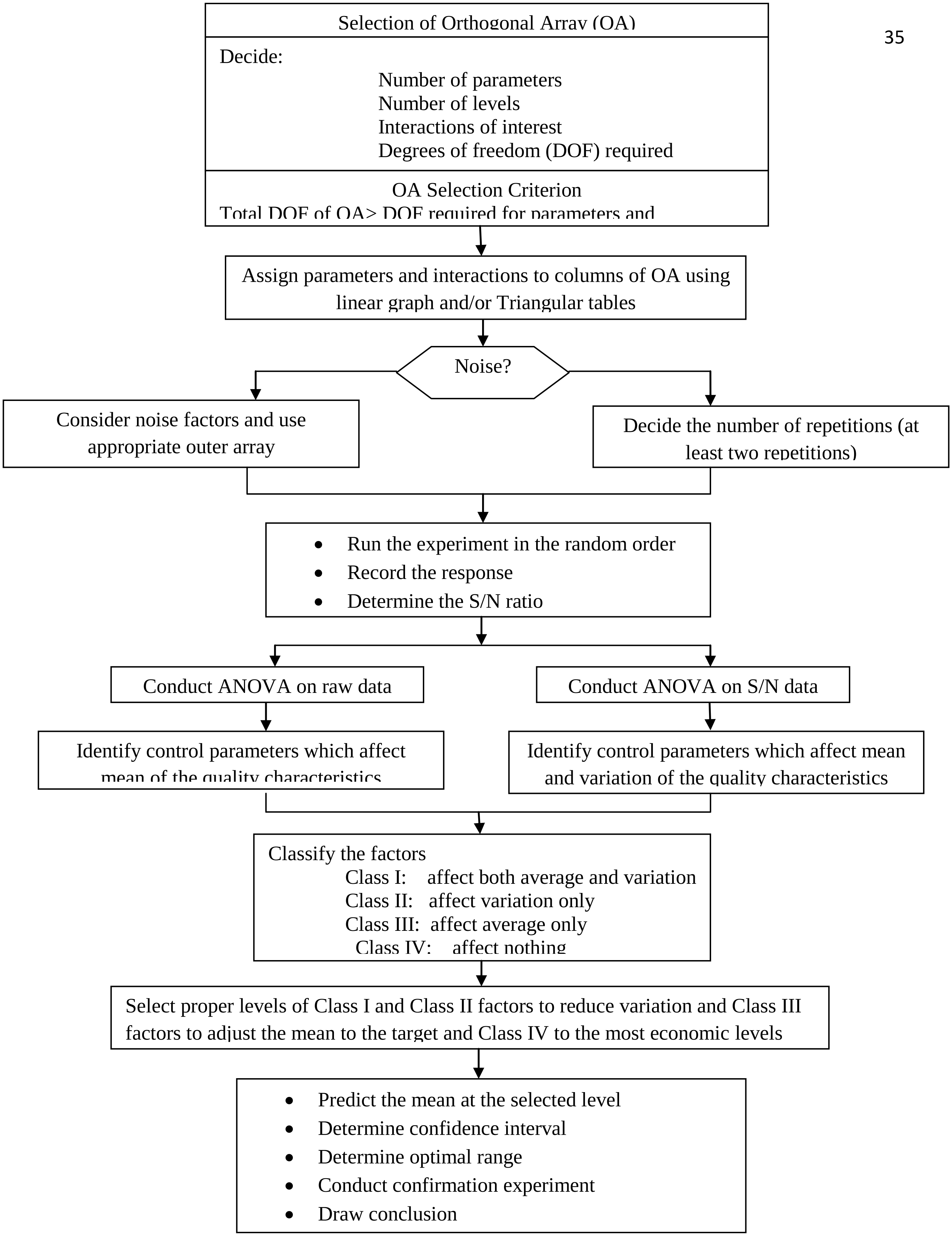


Figure 4.3 Taguchi Experimental Design and Analysis Flow Diagram

4.1.6 Experimentation and data collection

The experiment is performed against each of the trial conditions of the inner array. Each experiment at a trial condition is repeated simply (if outer array is not used) or according to the outer array (if used). Randomization should be carried to reduce bias in the experiment.

The data (raw data) are recorded against each trial condition and S/N ratios of the repeated data points are calculated and recorded against each trial condition.

4.1.7 Data analysis

A number of methods have been suggested by Taguchi for analyzing the data: observation method, ranking method, column effect method, ANOVA, S/N ANOVA, plot of average response curves, interaction graphs etc. (Ross, 1988). However, in the present investigation the following methods have been used:

- Plot of average response curves
- ANOVA for raw data
- ANOVA for S/N data
- S/N response graphs
- Interaction graphs
- Residual graphs

The plot of average responses at each level of a parameter indicates the trend. It is a pictorial representation of the effect of parameter on the response. The change in the response characteristic with the change in levels of a parameter can easily be visualized from these curves.

Typically, ANOVA for OA‟s are conducted in the same manner as other structured experiments (Ross, 1988).

The S/N ratio is treated as a response of the experiment, which is a measure of the variation within a trial when noise factors are present. A standard ANOVA can be conducted on S/N ratio which will identify the significant parameters (mean and variation). Interaction graphs are used to select the best combination of interactive parameters (Peace, 1993). Residual plots are used to check the accuracy.

4.1.8. Confirmation experiment

The confirmation experiment is a final step in verifying the conclusions from the previous round of experimentation. The optimum conditions are set for the significant parameters (the insignificant parameters are set at economic levels) and a selected number of tests are run under specified conditions. The average of the confirmation experiment results is compared with the anticipated average based on the parameters and levels tested. The confirmation experiment is a crucial step and is highly recommended to verify the experimental conclusion (Ross, 1988).

Chapter 5

Experimental Results and Analysis of Taguchi Design Method

5.1 Introduction

The present chapter deals with designed experiments based on Taguchi experimental design method to show the application of Taguchi method. The objective of the experiments wasto investigate the effect of process parameters on WEDM performance e.g. cutting speed, surface roughness, wire rupture and surface integrity. The experimental results are discussed subsequently in the following sections.

5.2 Parameters Selection

Selecting the input parameters and performance measures has to be determined before performing the experiments. In this work, the behaviors of seven control factors were studied. These parameters with their levels are listed in Table 1. Process parameters must be at least in three levels to reflect the true behavior of output parameters of study. Apart from parameters mentioned in Table 1, some machining parameters were kept constant during experiments in order to optimize the process. The machining parameters were chosen based on review of the literature and experience. Table 2 shows the fixed machining parameters.

The WEDM experiments were performed in order to study the effect of process parameters on the output response characteristics such as cutting speed and surface roughness. High productivity of WEDM is achieved with maximum amount of cutting speed and minimum amount of surface roughness. The S/N ratio and average value of the response characteristics for each variable at different levels were calculated from experimental data.

Regarding Taguchi experimental design approach Taguchi L18 design of experiment (DOE) was applied because there are one factor with two levels and six factors with three levels in the model. So, degree of freedom (DOF) for the first factor is one and for other factors is two. This gives a total of 13 DOF for seven process parameters selected in this work. Also, residual error has four DOF. Thus we have a total of 17 DOF for the factors as well as the residual error for the present experiments.

Symbols	**Parameters**	**Units**	**Level**		
			L1	**L2**	**L3**
A	Pulsewidth	μs	0.3	0.5	0.7
B	Timebetweentwo pulses	μs	14	18	22
Aj	Servo reference mean voltage	V	30	40	50
IAL	Striking Pulse Current	A	6	9	12
INJ	Injection pressure	bars	5	7	9
Wb	Wiremechanical Tension	daN(kg)	0.7	0.9	1.1
			L1	**L2**	
V	Voltage		-80	-100	

Table 5.1 Machining Parameters and Levels

Symbol	Machining parameters	Value
TAC	Short pulse time	0.3
S	Maximum rate of linear feed for machining	3
Ws	Wire feed speed (m/min)	15
M	Machining mode	1
FF		100

Table 5.2 Fixed Machining Parameter

5.3 Experimental Results

The WEDM experiments were performed in order to study the effect of process parameters on the output response characteristics with the process parameters as given in Table…. The experimental results are collected for cutting speed and surface roughness. 18 experiments were conducted using Taguchi experimental design method and there were two replicates for each experiment to obtain S/N values. In this study all the designs, plots and analysis were carried out using Minitab statistical software.

Larger cutting speed amount and lower amount of surface roughness show the high productivity of Wire EDM. Therefore, "the large better" formula and "the small better" formula are applied to calculate the S/N ratio of cutting speed and surface roughness respectively.

Column No.	V	IAL	A	B	Aj	INJ	Wb	Response	
								R1	R2
1	1 -80	1 6	1 0.3	1 14	1 30	1 5	1 0.7		
2	1 -80	1 6	2 0.5	2 18	2 40	2 7	2 0.9		
3	1 -80	1 6	3 0.7	3 22	3 50	3 9	3 1.1		
4	1 -80	2 9	1 0.3	1 14	2 40	2 7	3 1.1		
5	1 -80	2 9	2 0.5	2 18	3 50	3 9	1 0.7		
6	1	2	3	3	1	1	2		

	-80	9	0.7	22	30	5	0.9		
7	1 -80	3 12	1 0.3	2 18	1 30	3 9	2 0.9		
8	1 -80	3 12	2 0.5	3 22	2 40	1 5	3 1.1		
9	1 -80	3 12	3 0.7	1 14	3 50	2 7	1 0.7		
10	2 -100	1 6	1 0.3	3 22	3 50	2 7	2 0.9		
11	2 -100	1 6	2 0.5	1 14	1 30	3 9	3 1.1		
12	2 -100	1 6	3 0.7	2 18	2 40	1 5	1 0.7		
13	2 -100	2 9	1 0.3	2 18	3 50	1 5	3 1.1		
14	2 -100	2 9	2 0.5	3 22	1 30	2 7	1 0.7		
15	2 -100	2 9	3 0.7	1 14	2 40	3 9	2 0.9		
16	2 -100	3 12	1 0.3	3 22	2 40	3 9	1 0.7		
17	2 -100	3 12	2 0.5	1 14	3 50	1 5	2 0.9		
18	2 -100	3 12	3 0.7	2 18	1 30	2 7	3 1.1		

Table 5.3 Taguchi's L_{18} Standard Orthogonal Array

5.4 Analysis and Discussion of Results

The WEDM experiments and using the parametric approach of the Taguchi's method were conducted in this study. In this section, the influence of the various process parameters on the cutting speed and surface roughness for different experimental conditions is discussed. The S/N ratio and average value of the response characteristics for each variable at different levels were calculated from experimental data. The analysis of variance (ANOVA) of raw data and S/N data were performed to determine the significant and insignificant variables and to show their effects on the response characteristic. Then, the response curves (main effect) were plotted for raw data and S/N data in order to examine the parametric effects on the response characteristics. Finally, the optimal values of significant process parameters in terms of mean response characteristics are defined based on analyzing the ANOVA table and response curves.

5.4.1 Effect on Cutting Speed

Experiments were conducted using L18 OA to find the effect of process parameters on the cutting rate. The experiments were done for two types of materials, Titanium and D2 steel. Zinc coated wire and High speed brass wire were used as tools. The rate of cutting speed for each work piece and tool materials were collected in same experimental conditions.

First, ANOVA table was carried out for all process parameters to determine the significant ones. Then, pooled ANOVA table, response curves and interaction curves were plotted in order to detect the interaction between significant parameters. At last, the response table for mean shows the importance and contribution of each significant parameter on cutting speed.

5.4.1.1 Zinc Coated Wire and Titanium

Trial No.	Cutting Speed (inch/hour)		S/N Ratio
	R1	R2	
1	6.6	6.9	16.57964
2	10.16	10.4	20.23809
3	10.85	10.9	20.72852
4	7.9	7.9	17.95254
5	8.22	8.4	18.39049
6	12.7	13.4	22.30284
7	7.53	7.79	17.68082
8	9.28	9.46	19.43359
9	14.5	14.9	23.34393
10	5.01	5.1	14.07339
11	10.25	10.51	20.3219
12	12.7	13.28	22.26569
13	6.37	6.57	16.21497
14	10.35	10.11	20.19572
15	14.1	14.07	22.97512
16	6.3	6.6	16.18415

17	12.31	12.4	21.83668
18	12.04	12.5	21.77231

Table 5.4 Experimental Results

Form the following ANOVA tables it was found that machining voltage, servo reference voltage, injection pressure, wire feed rate and wire mechanical tension are non-significant process parameters for cutting speed because their P-value is more than 0.05. The pooled version of ANOVA for the raw data and S/N data for cutting speed is given in next tables. It is concluded from the ANOVA that Pulse width, peak current and time between two pulses significantly affect the variation in the cutting speed values.

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
V	1	0.036	0.036	0.0365	0.03	0.875
IAL	2	54.823	54.823	27.4115	21.20	0.039
A	2	102.489	102.489	51.2444	39.62	0.002
B	2	78.536	78.536	39.2684	30.37	0.013
Aj	2	2.118	2.118	1.0592	0.82	0.503
INJ	2	0.463	0.463	0.2314	0.18	0.843
Wb	2	0.672	0.672	0.3360	0.26	0.783
Residual Error	4	5.174	5.174	1.2934		
Total	17	244.311				

Table 5.5 Analysis of Variance for SN ratios

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
V	1	0.107	0.107	0.1073	0.10	0.765
IAL	2	87.757	87.757	43.8785	41.67	0.029
A	2	118.706	118.706	59.3528	56.37	0.001
B	2	74.2786	74.2786	37.1393	35.27	0.046
Aj	2	1.007	1.007	0.5035	0.48	0.651
INJ	2	0.992	0.992	0.4961	0.47	0.655
Wb	2	2.293	2.293	1.1464	1.09	0.419
Residual Error	4	4.212	4.212	1.0530		
Total	17	289.3526				

Table 5.6 Analysis of Variance for Means

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**

IAL	2	3.116	3.1160	1.5580	15.81	0.026
A	2	102.489	60.7050	30.3525	308.03	0.000
B	2	8.705	7.3116	3.6558	37.10	0.008
IAL*A	4	2.842	2.1876	0.5469	5.55	0.095
IAL*B	4	5.326	5.3259	1.3315	13.51	0.029
Residual Error	3	0.296	0.2956	0.0985		
Total	17	122.773				

Table 5.7 Pooled Analysis of Variance for SN ratios

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
IAL	2	3.519	3.5191	1.7596	10.47	0.044
A	2	118.706	68.0709	34.0354	202.52	0.001
B	2	11.104	8.3793	4.1897	24.93	0.014
IAL*A	4	1.771	1.0565	0.2641	1.57	0.370
IAL*B	4	6.335	6.3355	1.5839	9.42	0.048
Residual Error	3	0.504	0.5042	0.1681		
Total	17	141.940				

Table 5.8 Pooled Analysis of Variance for Means

Based on the results in the Tables 5.7 and 5.8, there is not any interaction between pulse width and peak current but there is a significant interaction between peak current and time between two pulses.

The tables include ranks based on delta statistics, which compares the relative magnitude of effects. The delta statistic is the highest average minus the lowest average for each factor. Minitab assigns ranks based on delta values in descending order; the highest delta value has rank 1 and rank 2 is assigned to the second highest, and so on. The ranks indicate the relative importance of each factor to the response. Pulse width has the maximum effect on cutting speed followed by time between two pulses and peak current.

Level	IAL	A	B
1	9.388	6.714	11.028
2	10.008	10.154	9.663
3	10.468	12.995	9.172
Delta	1.079	6.281	1.857
Rank	3	1	2

Table 5.9 Response Table for Means

Figures 5.1 and 5.2 indicate that there is a negligible interaction between the time between two pulses and peak current in affecting the cutting rate since the responses at different levels of process parameters for a given level of parameter value are almost parallel. Also, the trend of peak current and pulse width in different levels stay the same. On the other hand, peak current and pulse width have interaction in affecting the cutting.

Figures 5.3 and 5.4 show that if pulse width and peak current increase, the cutting speed increases. Also, it shows that, with increase in time between two pulses the cutting rate decreases. This is because of the increase in discharge energy and enhancement in pulse width and peak current that lead to a faster cutting rate. The number of discharges within a given period becomes smaller because the time between two pulses increases which leads to a lower cutting rate. It is also evident that cutting speed at the first level of pulse width and peak current is the minimum and at the first levels of time between two pulses is the maximum.

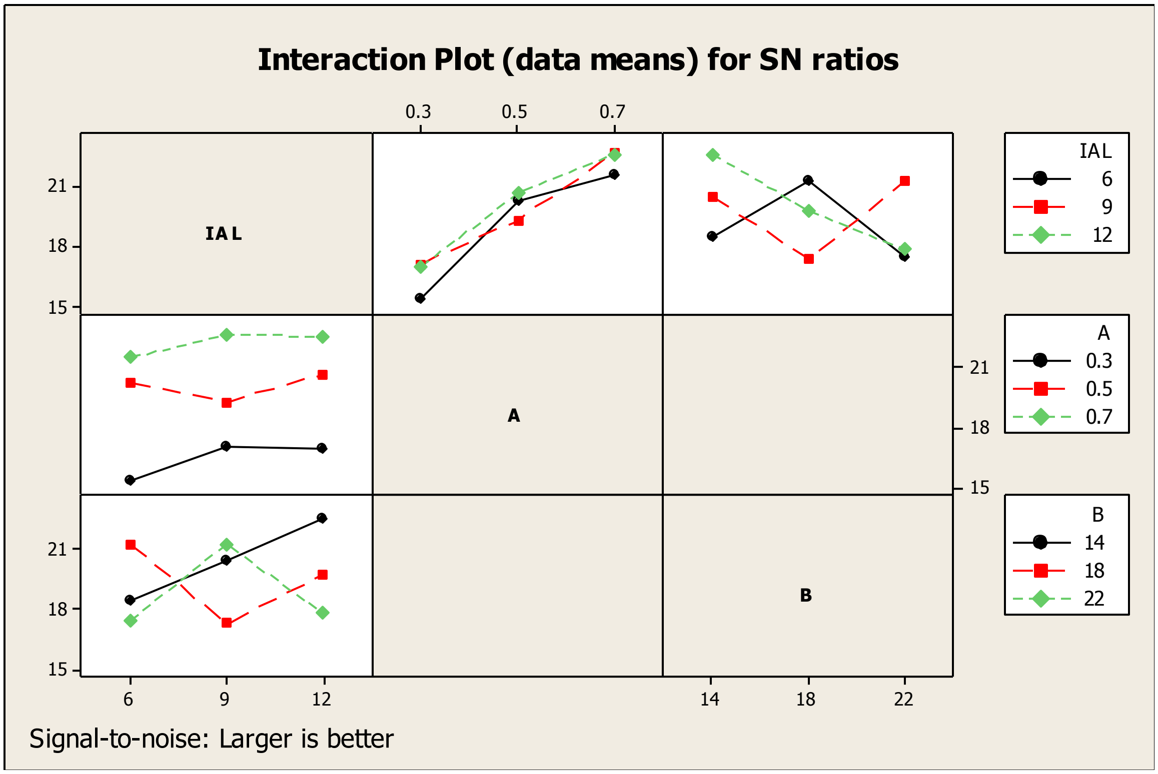


Figure 5.1 Effect of Process Parameters Interaction on Cutting Speed (S/N Data)

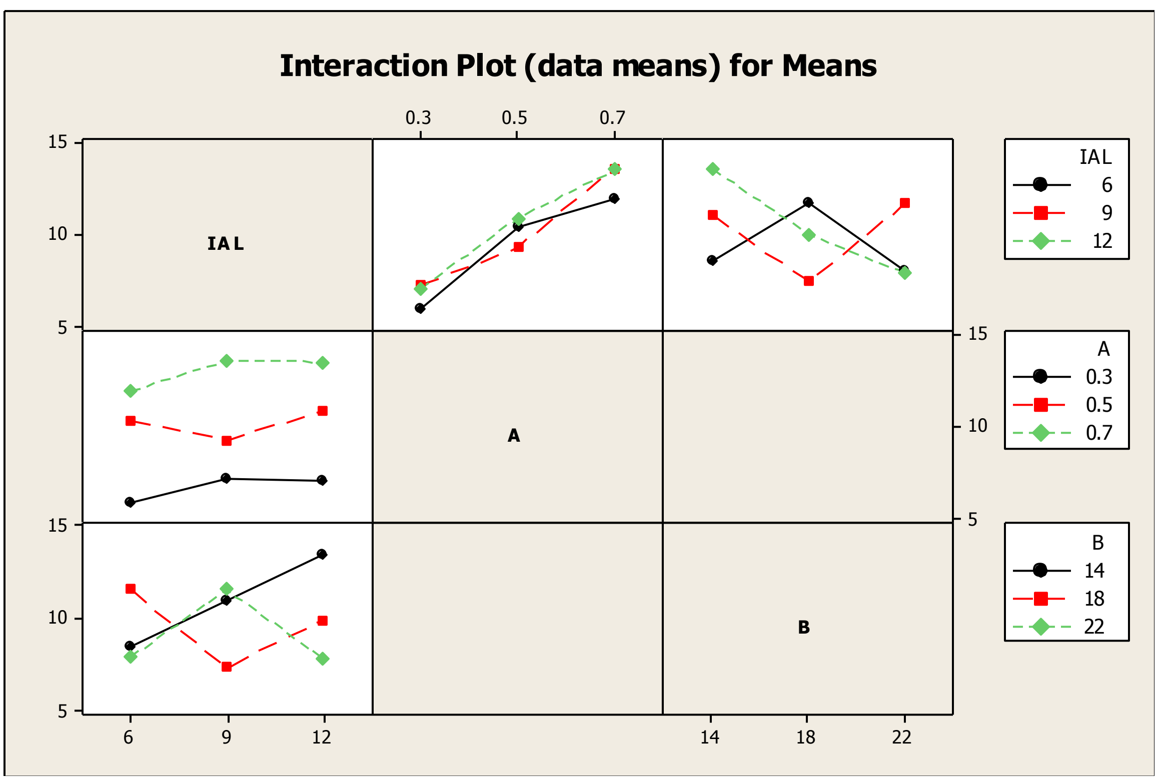


Figure 5.2 Effect of Process Parameters Interaction on Cutting Speed (Raw Data)

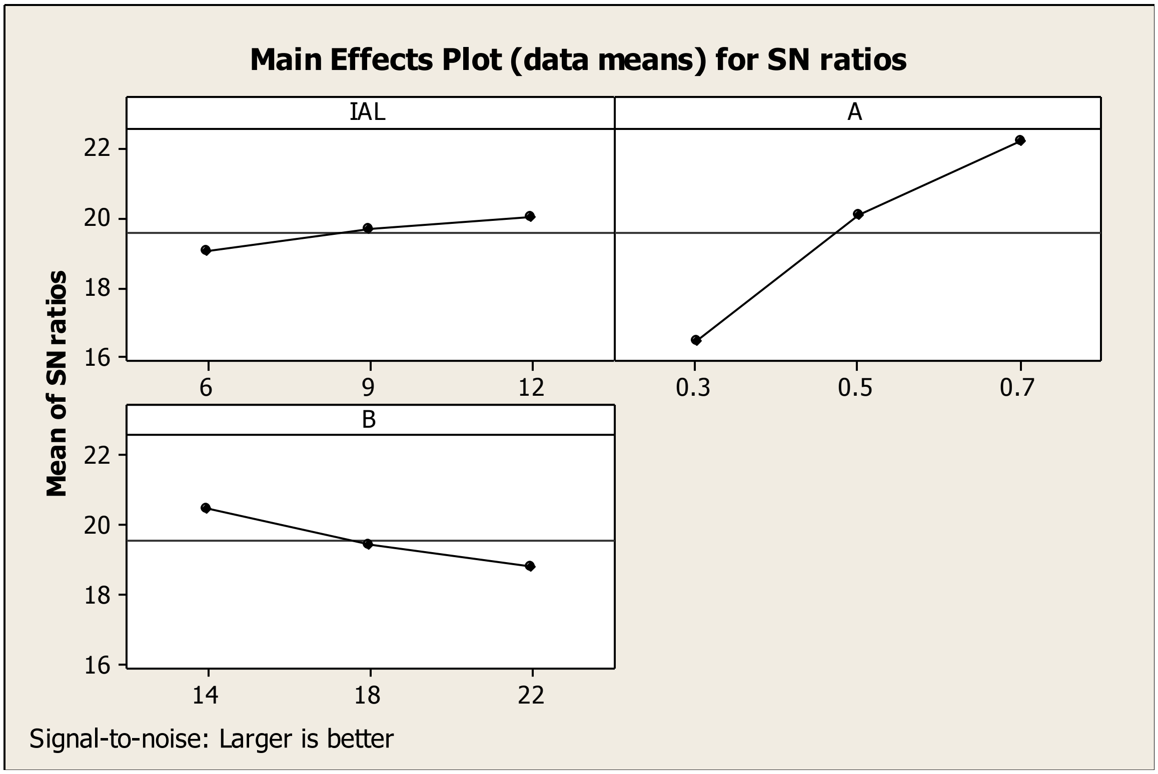


Figure 5.3 Effects of Process Parameters on Cutting Speed (S/N Data)

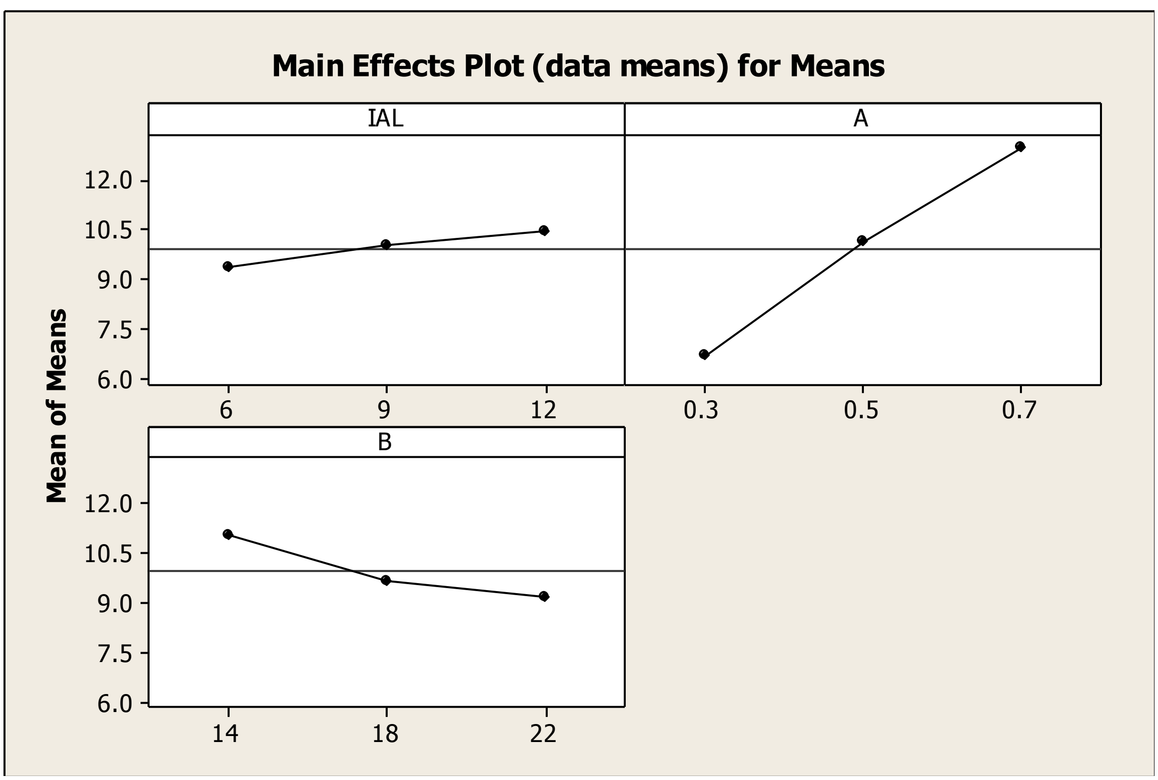


Figure 5.4 Effects of Process Parameters on Cutting Speed (Raw Data)

5.4.1.1.1 Selection of Optimal Levels

It can be seen that the third level of peak current (IAL_3), the first level of time between two pulses (B_1), and the third level of pulse width (A_3) provide the maximum value of cutting speed. The same levels of the variables (A_3, B_1, and IAL_3) as the best levels for the maximum cutting speed in WEDM process are achieved by S/N data analysis.

5.4.1.2 High-speed Brass Wire and Titanium

Trial No.	Cutting Speed (inch/hour)		S/N Ratio
	R1	R2	
1	4.83	5.01	13.83494
2	7.40	7.63	17.51553
3	7.90	7.90	17.95254
4	5.50	5.60	14.8848
5	6.90	7.20	16.95788
6	9.32	9.54	19.48846
7	5.13	5.20	14.26081
8	7.20	7.40	17.26401
9	10.22	10.45	20.2846
10	3.04	3.10	9.741523
11	7.02	7.20	17.0353
12	9.60	10.10	19.86033
13	4.03	4.15	12.23166
14	7.80	7.66	17.76252
15	10.10	10.00	20.043
16	4.05	4.05	12.1491
17	8.75	8.80	18.86484
18	8.30	8.90	18.67411

Table 5.10 Experimental Results

In order to find the significance of the process parameters towards cutting speed ANOVA table was performed. From the Tables 5.11 and 5.12 it is evident that machining voltage, servo reference voltage, injection pressure, wire feed rate and wire mechanical tension are non-significant process parameters for cutting speed. On the other hand, it is found from the ANOVA that pulse width, peak current and time between two pulses significantly affect the variation in the cutting speed values. Then, the pooled version of ANOVA of the raw data and S/N data for cutting speed is given in next tables. In pooled ANOVA table the non-significant parameters were removed and the interaction between significant parameters was investigated.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	1	2.054	2.054	2.0545	1.82	0.249
IAL	2	75.7317	75.7317	37.865	33.48	0.033
A	2	136.459	136.459	68.2296	60.30	0.001
B	2	99.347	99.347	49.6735	44.13	0.016
Aj	2	3.221	3.221	1.6104	1.42	0.341
INJ	2	0.961	0.961	0.4805	0.42	0.680
Wb	2	0.681	0.681	0.3405	0.30	0.756
Residual Error	4	4.526	4.526	1.1316		
Total	17	322.9627				

Table 5.11 Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	1	0.1881	0.1881	0.1881	0.51	0.516
IAL	2	23.5279	23.5279	11.7639	32.05	0.024
A	2	73.3942	73.3942	36.6971	98.56	0.000
B	2	10.4707	10.4707	5.2353	16.00	0.042
Aj	2	0.8022	0.8022	0.4011	1.08	0.422
INJ	2	0.7704	0.7704	0.3852	1.03	0.434
Wb	2	1.3000	1.3000	0.6500	1.75	0.285
Residual Error	4	1.4893	1.4893	0.3723		
Total	17	111.9428				

Table 5.12 Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
IAL	2	23.354	23.354	11.6768	15.27	0.041
A	2	136.459	86.043	43.0214	58.31	0.004
B	2	46.347	46.585	23.2925	32.17	0.025
IAL*A	4	2.910	3.113	0.7784	1.05	0.503
IAL*B	4	6.320	6.320	1.5799	2.14	0.279
Residual Error	3	2.214	2.214	0.7379		
Total	17	217.604				

Table 5.13 Pooled Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
IAL	2	4.05279	4.05279	2.0639	13.84	0.036
A	2	73.3942	44.0508	22.0254	197.32	0.001
B	2	4.4707	4.7552	2.3776	21.30	0.017
IAL*A	4	0.9069	0.7514	0.1878	1.68	0.349
IAL*B	4	3.3082	3.3082	0.8270	7.41	0.066
Residual Error	3	0.3349	0.3349	0.1116		
Total	17	86.4677				

Table 5.14 Pooled Analysis of Variance for Means

Tables 5.13 and 5.14 show there is not any interaction between pulse width and time between two pulses with peak current.

The rank table indicates the relative importance of significant factors to the response is same as the previous experiments results for Titanium and Zinc coated wire. Pulse width has the maximum effect on cutting speed followed by time between two pulses and peak current. Also, the same factors (peak current, time between two pulses and pulse width) are the only significant process parameters for Titanium and brass wire same as experiment results for Titanium and Zinc coated wire.

Level	IAL	A	B
1	6.728	4.474	7.790
2	7.317	7.580	7.045
3	7.371	9.361	6.580
Delta	0.643	4.887	1.210
Rank	3	1	2

Table 5.15 Response Table for Means

It is seen from Figures 5.5 and 5.6 that there is not any interaction between peak current and pulse width in affecting the cutting rate since the responses at different levels of process parameters for a given level of parameter value are almost parallel. But, there is a slight interaction between peak current and time between two pulses. These results confirm the results that are achieve from ANOVA and pooled ANOVA tables.

Based on Figures 5.7 and 5.8 the cutting speed increases with the increase of pulse width and peak current. The reason is that the discharge energy increases with the pulse width and peak current causing cutting speed improvement. Increase in time between two pulses leads to decrease in cutting speed due to reduction in the number of discharges within a given period. It is also evident that cutting rate is minimum at the first level of pulse width and maximum at the first level of time between two pulses.

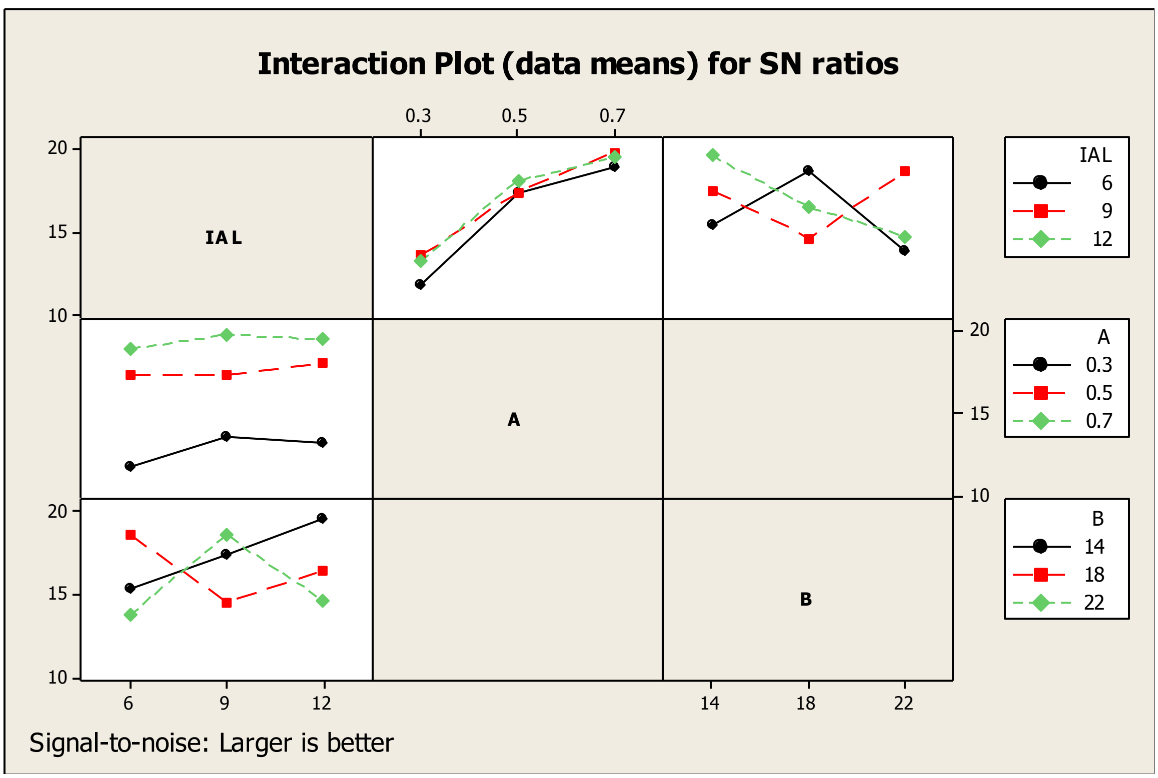


Figure 5.5 Effects of Process Parameters Interaction on Cutting Speed (S/N Data)

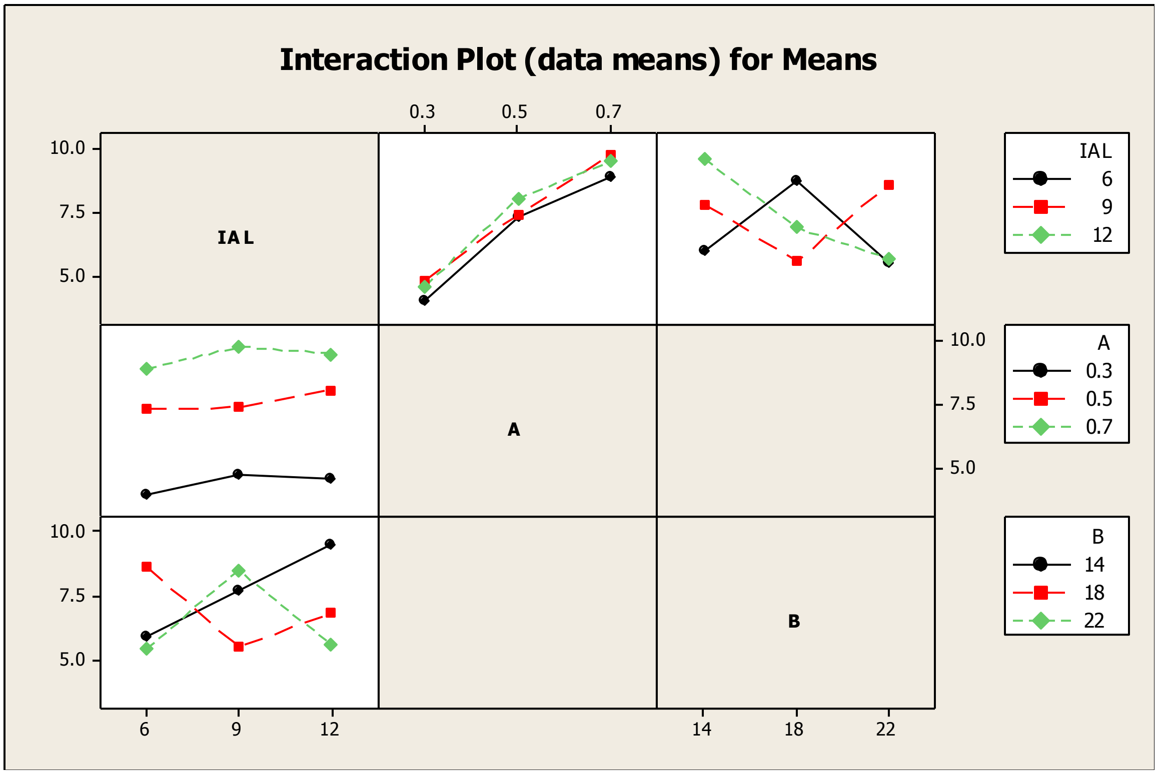


Figure 5.6 Effects of Process Parameters Interaction on Cutting Speed (Raw Data)

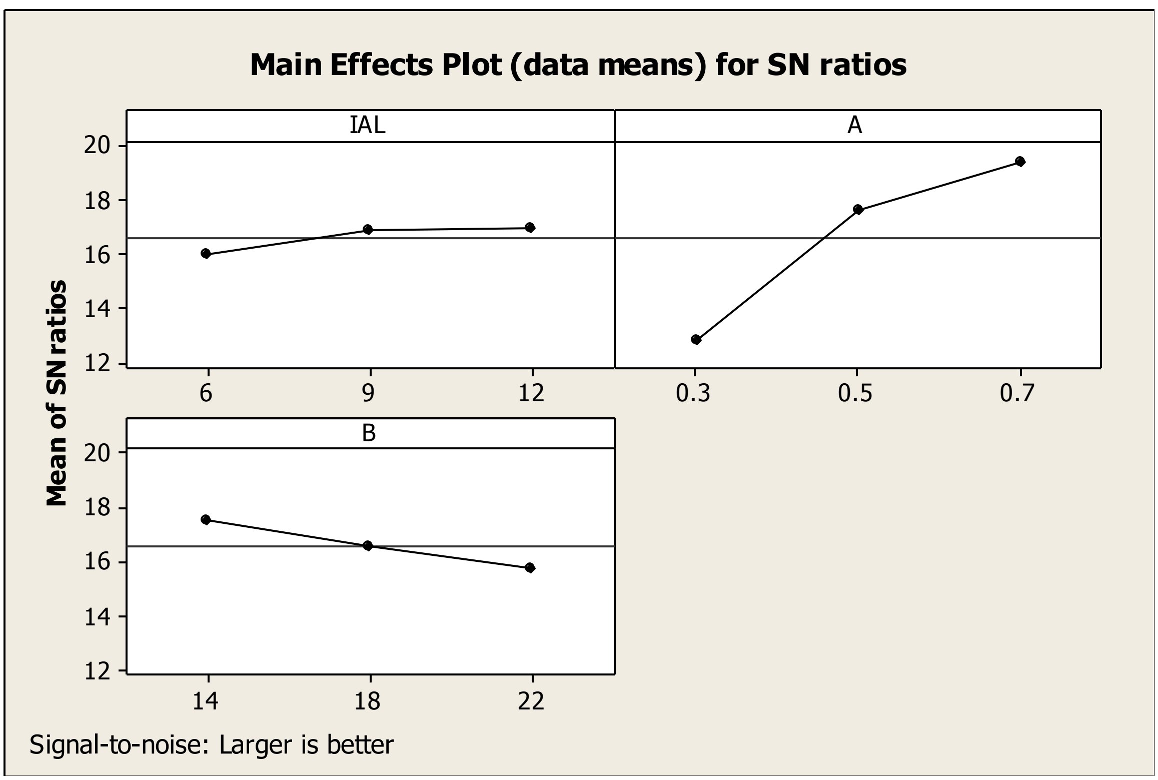


Figure 5.7 Effects of Process Parameters on Cutting Speed (S/N Data)

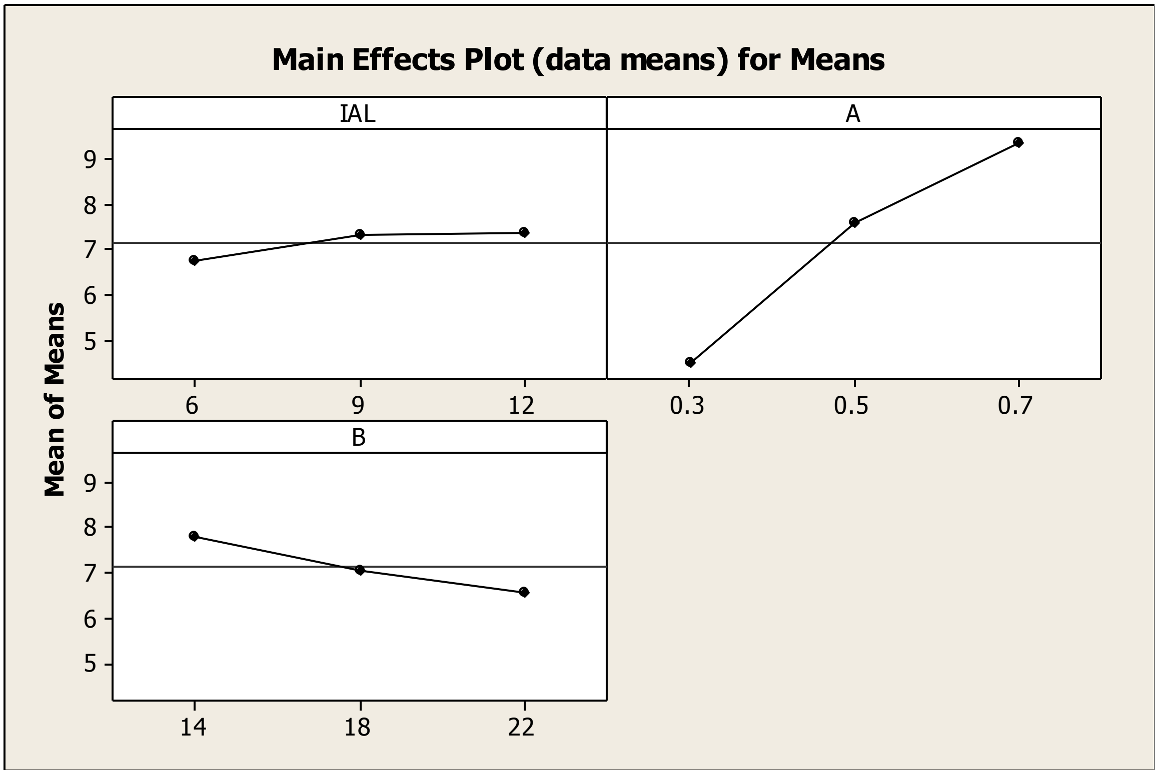


Figure 5.8 Effects of Process Parameters on Cutting Speed (Raw Data)

5.4.1.2.1 Selection of Optimal Levels

The highest levels of the significant parameters give the optimal value of cutting speed. Therefore, it can be seen that the third level of peak current (IAL_3), the first level of time between two pulses (B_1) and the third level of pulse width (A_3) provide the maximum value of cutting speed. The S/N data analysis also confirms the same levels of the variables (A_3, B_1, and IAL_3) as the best levels for the maximum cutting speed in WEDM process.

5.4.1.3 High-speed Brass and Steel

Trial No.	Cutting Speed (inch/hour)		S/N Ratio
	R1	R2	
1	5.00	5.20	14.14639
2	5.60	5.71	15.04742
3	5.50	5.53	14.83081
4	4.20	4.45	12.70884

5	4.00	4.10	12.14711
6	8.57	8.66	18.70475
7	4.00	4.00	12.0412
8	4.90	5.05	13.9329
9	8.70	8.86	18.86881
10	2.55	2.89	8.640451
11	8.30	8.30	18.38156
12	9.30	9.43	19.42953
13	3.28	3.32	10.3698
14	5.90	5.90	15.41704
15	10.80	10.95	20.72797
16	3.14	3.18	9.99322
17	7.15	7.76	17.42714
18	10.16	10.43	20.25029

Table 5.16 Experimental Results

It was found from Tables 5.17 and 5.18, that machining pulse width, servo reference mean voltage and time between two pulses significantly affect the variation in the cutting speed values. The rest of the parameters are non-significant as revealed from the following tables. Also, the pooled ANOVA tables (5.19 and 5.20) were performed to investigate significant parameters and their relations.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	1	0.1242	0.1242	0.1242	1.27	0.354
IAL	2	0.96	0.96	0.48	4.91	0.166
A	2	168.536	168.536	84.2678	861.42	0.000
B	2	36.605	36.605	18.3023	187.09	0.000
Aj	2	23.289	23.289	11.6445	119.04	0.000
INJ	2	0.633	0.633	0.3163	3.23	0.146
Wb	2	0.7393	0.7393	0.3698	3.78	0.14
Residual Error	4	0.391	0.391	0.0978		
Total	17	231.2775				

Table 5.17 Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	1	0.2482	0.2482	0.2482	3.13	0.154
IAL	2	0.376	0.3760	0.1880	2.37	0.209
A	2	79.576	79.5761	39.7881	501.80	0.000
B	2	16.376	16.3755	8.1878	103.26	0.000
Aj	2	9.196	9.1955	4.5978	57.99	0.001

INJ	2	0.874	0.8739	0.4369	5.51	0.071
Wb	2	0.717	0.7171	0.3585	4.52	0.094
Residual Error	4	0.317	0.3172	0.0793		
Total	17	107.6802				

Table 5.18 Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	168.536	168.536	84.2678	105.02	0.002
B	2	36.605	30.894	15.4469	19.25	0.019
Aj	2	24.289	16.977	8.4884	10.33	0.042
A*B	4	4.529	3.242	0.8105	1.01	0.518
A*Aj	4	1.293	1.293	0.3232	0.40	0.800
Residual Error	3	2.407	2.407	0.8024		
Total	17	237.659				

Table 5.19 Pooled Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	79.576	79.5761	39.7881	230.28	0.001
B	2	16.376	14.9946	7.4973	43.39	0.006
Aj	2	9.196	7.3546	3.6773	21.28	0.017
A*B	4	5.449	2.7285	0.6821	3.95	0.144
A*Aj	4	2.274	2.2740	0.5685	3.29	0.178
Residual Error	3	0.518	0.5183	0.1728		
Total	17	113.388				

Table 5.20 Pooled Analysis of Variance for Means

Minitab assigns rank 1 to pulse width, rank 2 to time between two pulses and rank 3 to servo references. On the other word, pulse width has the maximum effect on cutting speed followed by time between two pulses and servo reference mean voltage.

Level	A	B	Aj
1	3.768	7.473	7.035
2	6.056	6.111	6.393
3	8.908	5.148	5.303
Delta	5.140	2.325	1.732
Rank	1	2	3

Table 5.21 Response Table for Means

The cutting rate is the minimum at the first level of pulse width time and the maximum at the first level of time between two pulses. It is seen from the Figures 5.9 and 5.10 that there is not any interaction between the process parameters in affecting the cutting rate since the responses at different levels of process parameters for a given level of parameter value are almost parallel.

Thus, all results are attained based on the ANOVA and pooled ANOVA tables are the same as the plots results.

From Figures 5.11 and 5.12 it is evident that the cutting rate increases with the increase of pulse width, and decreases with the increase in time between two pulses and servo reference mean voltage. This is because the discharge energy increases with the pulse width leading to a faster cutting rate. As the time between two pulses decreases, the number of discharges within a given period becomes more which leads to a higher cutting rate. With increase in servo reference mean voltage the average discharge gap gets widened resulting into a lower cutting rate.

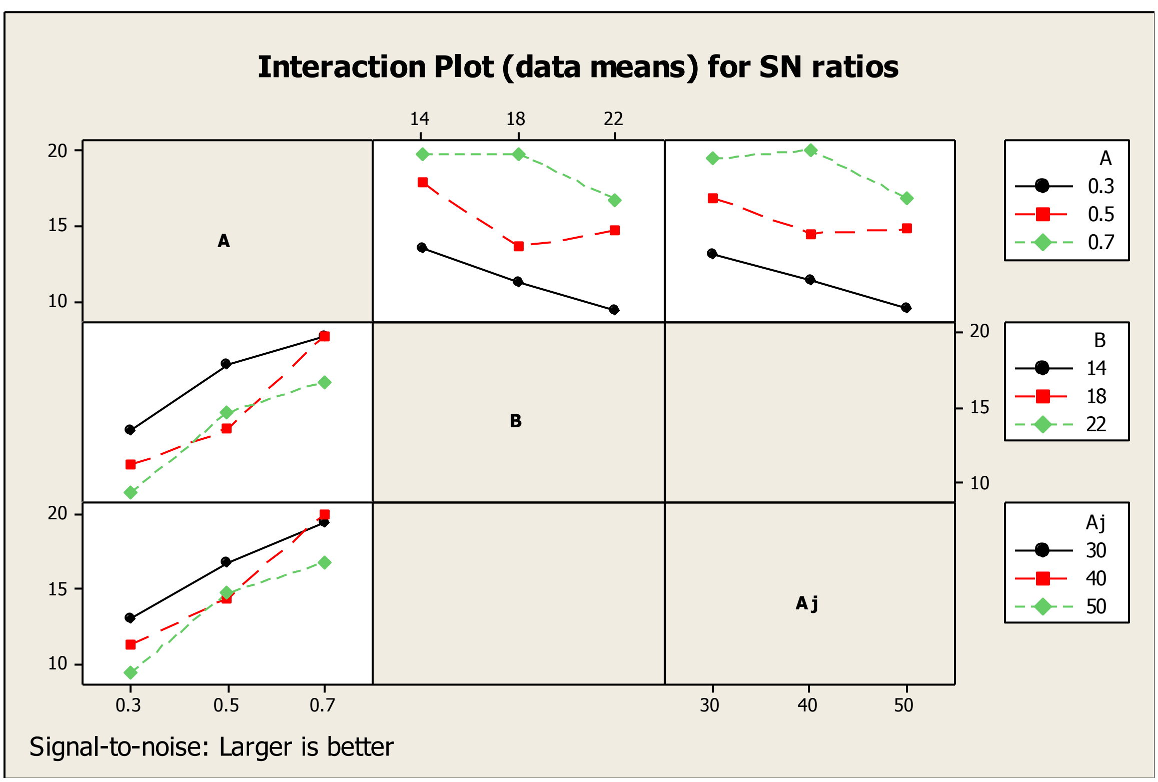


Figure 5.9 Effects of Process Parameters Interaction on Cutting Speed (S/N Data)

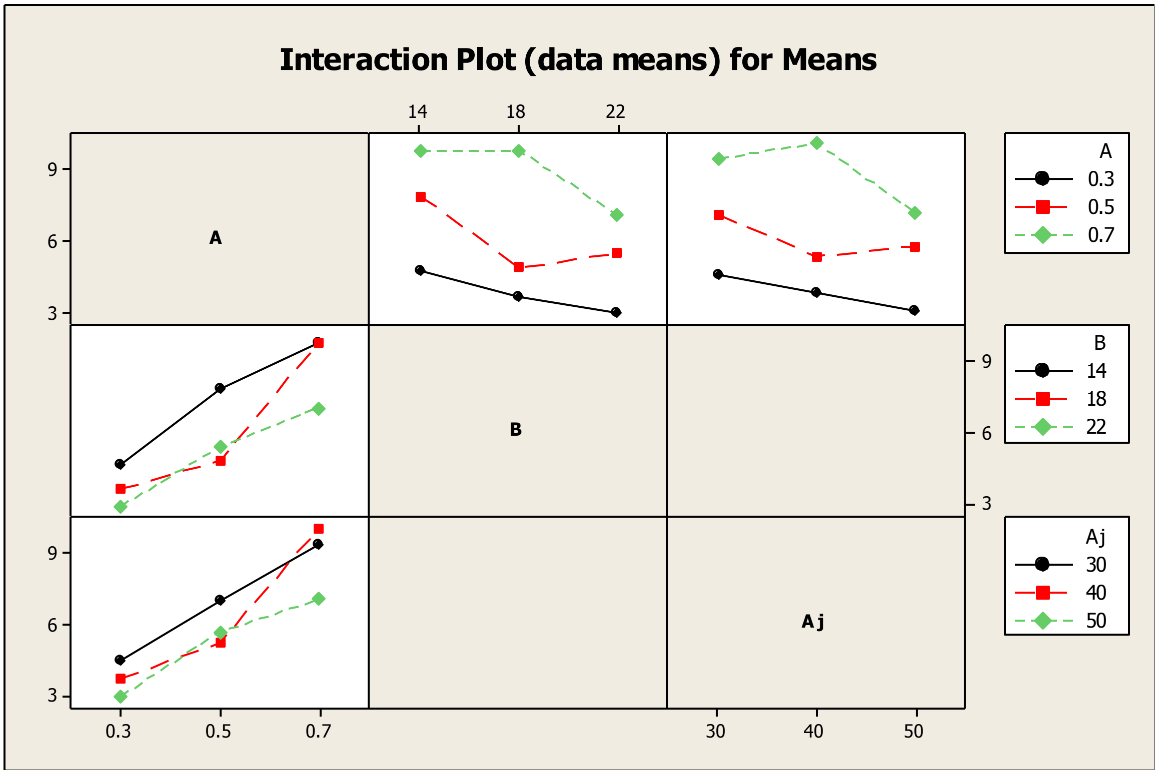


Figure 5.10 Effects of Process Parameters Interaction on Cutting Speed (Raw Data)

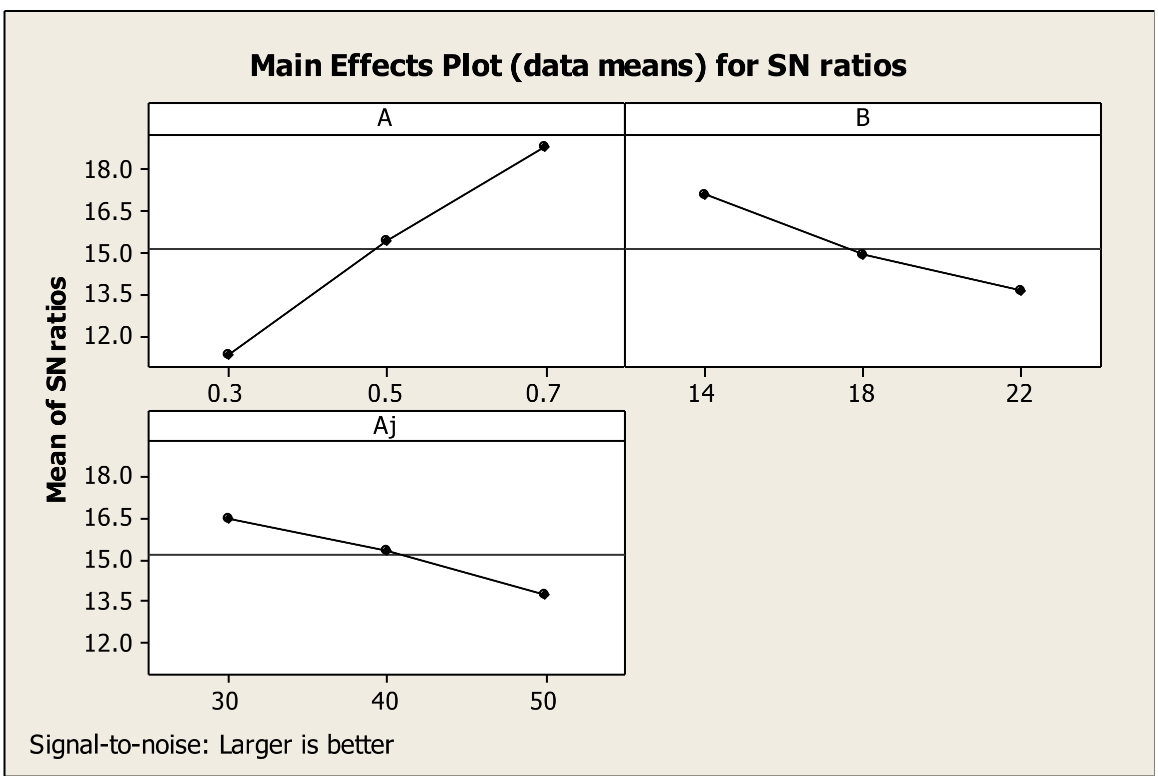


Figure 5.11 Effects of Process Parameters on Cutting Speed (S/N Data)

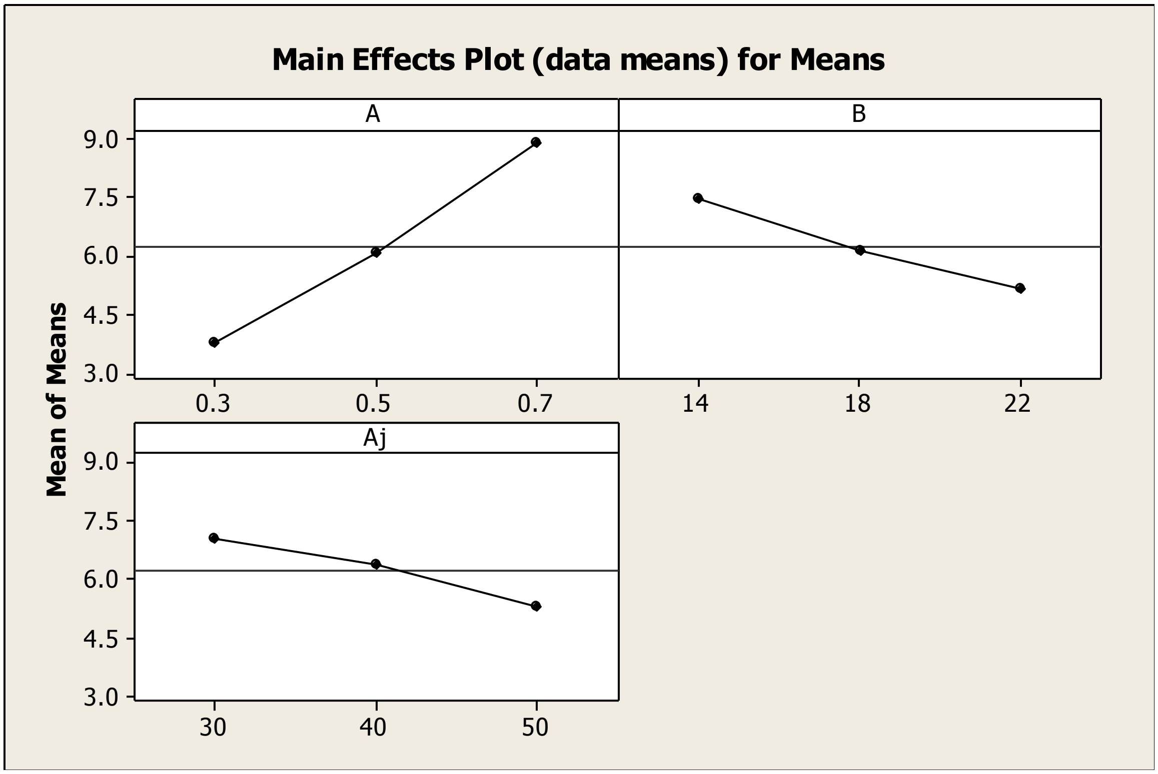


Figure 5.12 Effects of Process Parameters on Cutting Speed (Raw Data)

5.4.1.3.1 Selection of Optimal Levels

It can be seen that the raw data and S/N data analysis suggest the first level of servo reference mean voltage (Aj_1), the first level of time between two pulses (B_1), and the third level of pulse width (A_3) to achieve the maximum value of cutting speed in WEDM process.

5.4.1.4 Zinc-Coated Wire and D2-Steel

Trial No.	Cutting Speed (inch/hour)		S/N Ratio
	R1	R2	
1	6.84	6.74	16.63669
2	7.9	7.95	17.97986
3	8	8	18.0618
4	5.9	5.86	15.3874
5	6	6	15.56303
6	11.38	11.58	21.19785
7	5.6	5.87	15.16345
8	6.9	7.1	16.8993

9	11.4	11.6	21.21297
10	3.52	3.94	11.39286
11	10.54	10.64	20.49763
12	12	12.22	21.66181
13	4.6	4.6	13.25516
14	8.4	8.3	18.43326
15	13.4	13.54	22.587
16	4.44	4.32	12.82704
17	9.94	9.96	19.95645
18	12.5	12.65	21.9897

Table 5.22 Experimental Results

The ANOVA table was performed to find the significance of the process parameters towards cutting speed. It was found that machining voltage, peak current, injection pressure, wire feed rate and wire mechanical tension are non-significant process parameters for cutting speed.

The pooled version of ANOVA of the raw data and S/N data for cutting speed is given in the next tables. It is concluded from the ANOVA Tables 5.23 and 5.24 that pulse width, servo reference mean voltage and time between two pulses significantly affect the variation in the cutting speed values.

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
V	1	1.124	1.124	1.1243	3.72	0.126
IAL	2	0.332	0.332	0.1662	0.55	0.615
A	2	148.814	148.814	74.4072	246.09	0.000
B	2	25.837	25.837	12.9183	42.72	0.002
Aj	2	17.512	17.512	8.7562	28.96	0.004
INJ	2	2.071	2.071	1.0353	3.42	0.136
Wb	2	0.479	0.479	0.2393	0.79	0.513
Residual Error	4	1.209	1.209	0.3024		
Total	17	197.379				

Table 5.23 Analysis of Variance for SN ratios

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
V	1	0.1782	0.1782	0.1782	4.40	0.1
IAL	2	0.346	0.346	0.1731	4.28	0.102
A	2	120.471	120.471	60.2354	1487.62	0.000
B	2	19.645	19.645	9.8223	242.58	0.000
Aj	2	11.624	11.624	5.8119	143.54	0.000

INJ	2	0.2851	0.2851	0.1425	3.52	0.15
Wb	2	0.3264	0.3264	0.1632	4.03	0.12
Residual Error	4	0.162	0.162	0.0405		
Total	17	153.0377				

Table 5.24 Analysis of Variance for Means

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
A	2	148.814	148.814	74.4072	93.77	0.002
B	2	25.837	19.670	9.8350	12.39	0.035
Aj	2	15.7113	15.7113	7.8556	9.90	0.046
A*B	4	2.370	2.119	0.5297	0.67	0.657
A*Aj	4	0.465	0.465	0.1162	0.15	0.953
Residual Error	3	2.381	2.381	0.7935		
Total	17	195.5783				

Table 5.25 Pooled Analysis of Variance for SN ratios

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
A	2	120.471	120.471	60.2354	131.97	0.001
B	2	19.645	16.655	8.3275	18.24	0.021
Aj	2	11.624	9.057	4.5287	9.92	0.048
A*B	4	4.661	2.423	0.6057	1.33	0.425
A*Aj	4	1.915	1.915	0.4788	1.05	0.505
Residual Error	3	1.369	1.369	0.4564		
Total	17	159.685				

Table 5.26 Pooled Analysis of Variance for Means

The P-value of interaction terms are more than 0.05 in pooled ANOVA tables. This indicates there is not any interaction between peak current with servo reference voltage and time between two pulses.

The following table includes ranks based on delta statistics, which compare the relative magnitude of effects. Pulse width has the maximum influence on cutting speed followed by the time between two pulses and servo reference mean voltage. In fact, pulse width has the highest importance for cutting speed among other significant parameters.

Level	**A**	**B**	**Aj**

1	5.186	9.697	9.253
2	8.303	8.158	8.461
3	11.523	7.157	7.297
Delta	6.337	2.540	1.957
Rank	1	2	3

Table 5.27 Response Table for Means

It is seen from Figures 5.13 and 5.14 that there is not any interaction between the process parameters in affecting the cutting rate since the responses at different levels of process parameters for a given level of parameter value are almost parallel.

Figure 5.15 and 5.16 show that when the pulse width increases the cutting speed increase because the discharge energy increases. On the other hand, the cutting speed decreases with increase in time between two pulses and servo reference mean voltage. This is because the number of discharges within a given period becomes more when the time between two pulses decreases. With increase in servo reference mean voltage the average discharge gap gets widened resulting into a lower cutting rate. It is also evident that the lowest amount of cutting speed is at the first level of pulse width time and its highest level is at the first level of time between two pulses and servo reference voltage.

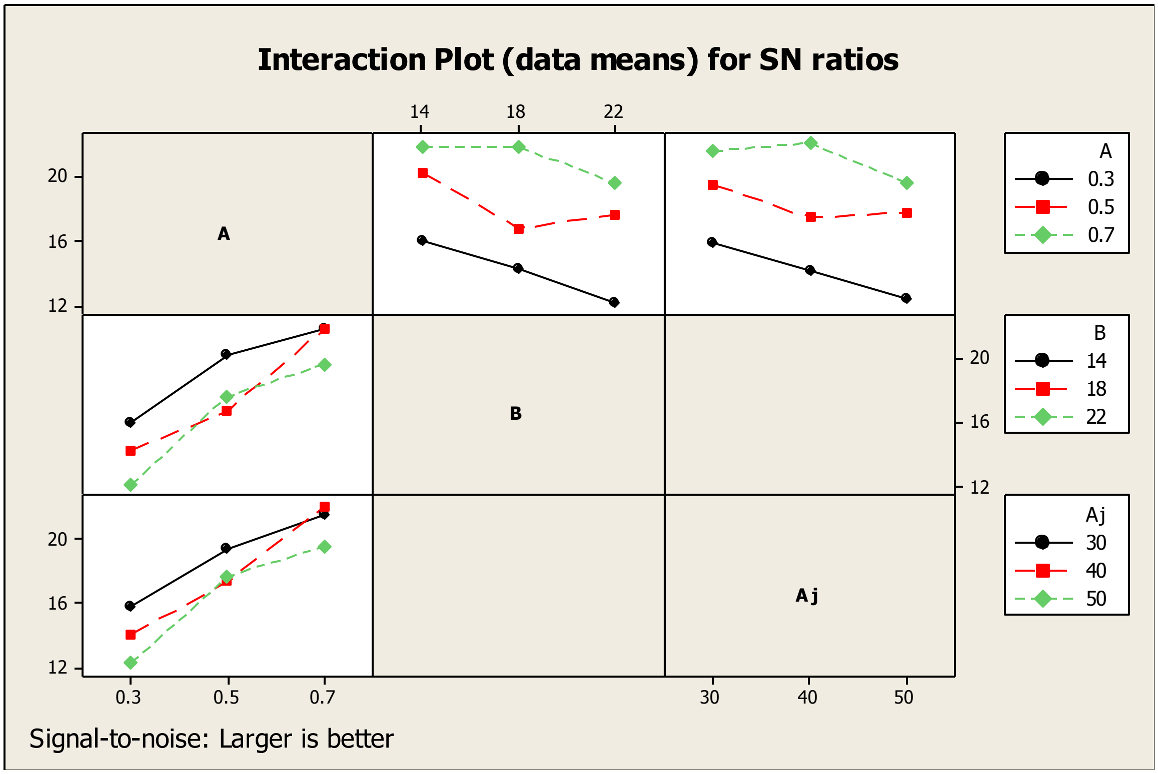


Figure 5.13 Effects of Process Parameters Interaction on Cutting Speed (S/N Data)

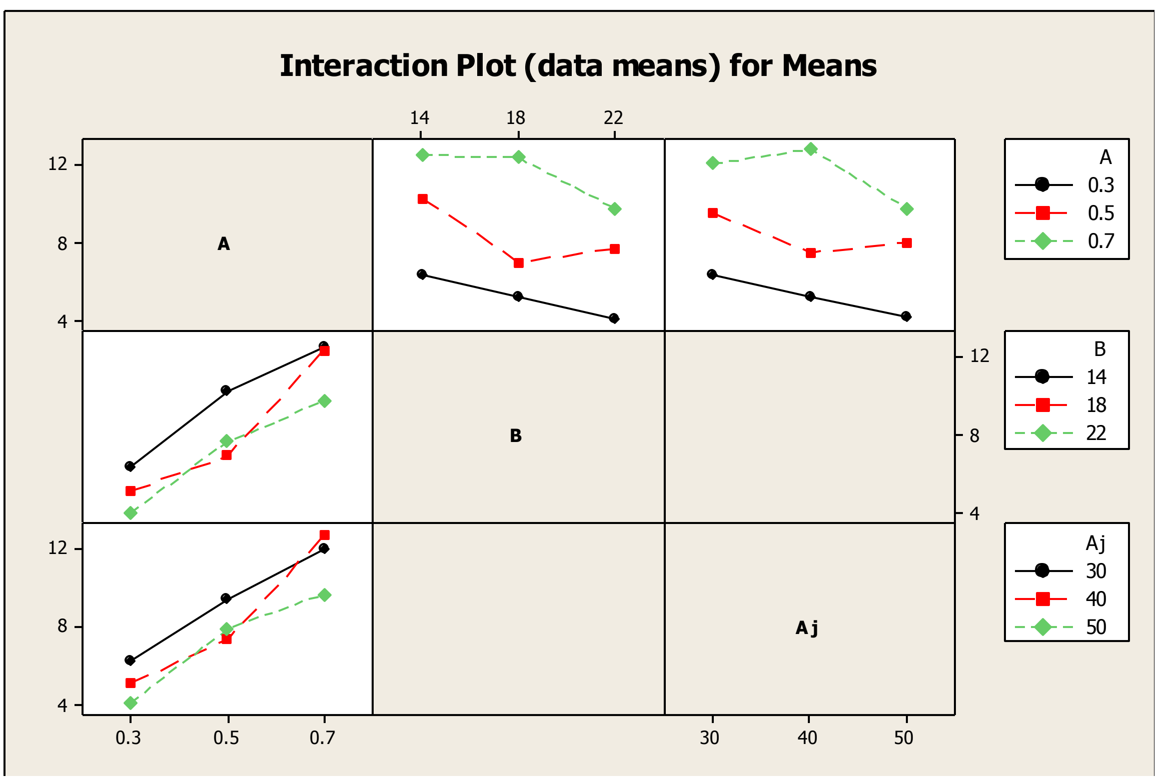


Figure 5.14 Effects of Process Parameters Interaction on Cutting Speed (Raw Data)

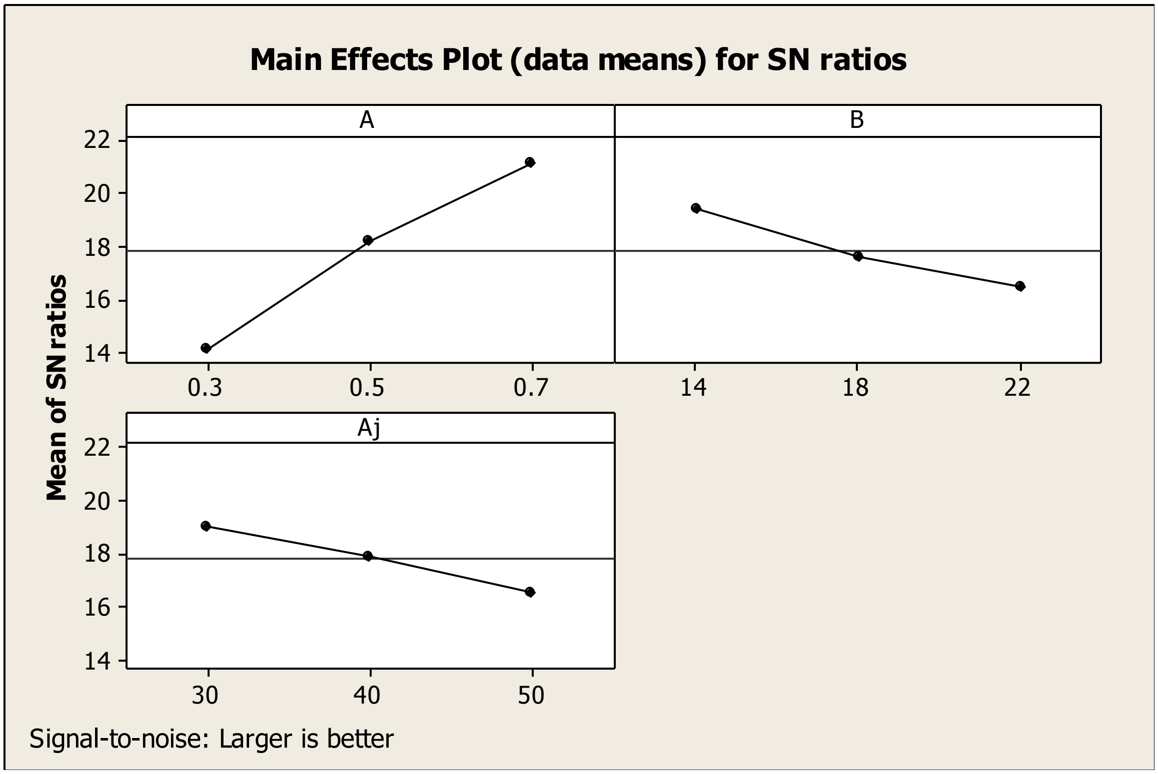


Figure 5.15 Effects of Process Parameters on Cutting Speed (S/N Data)

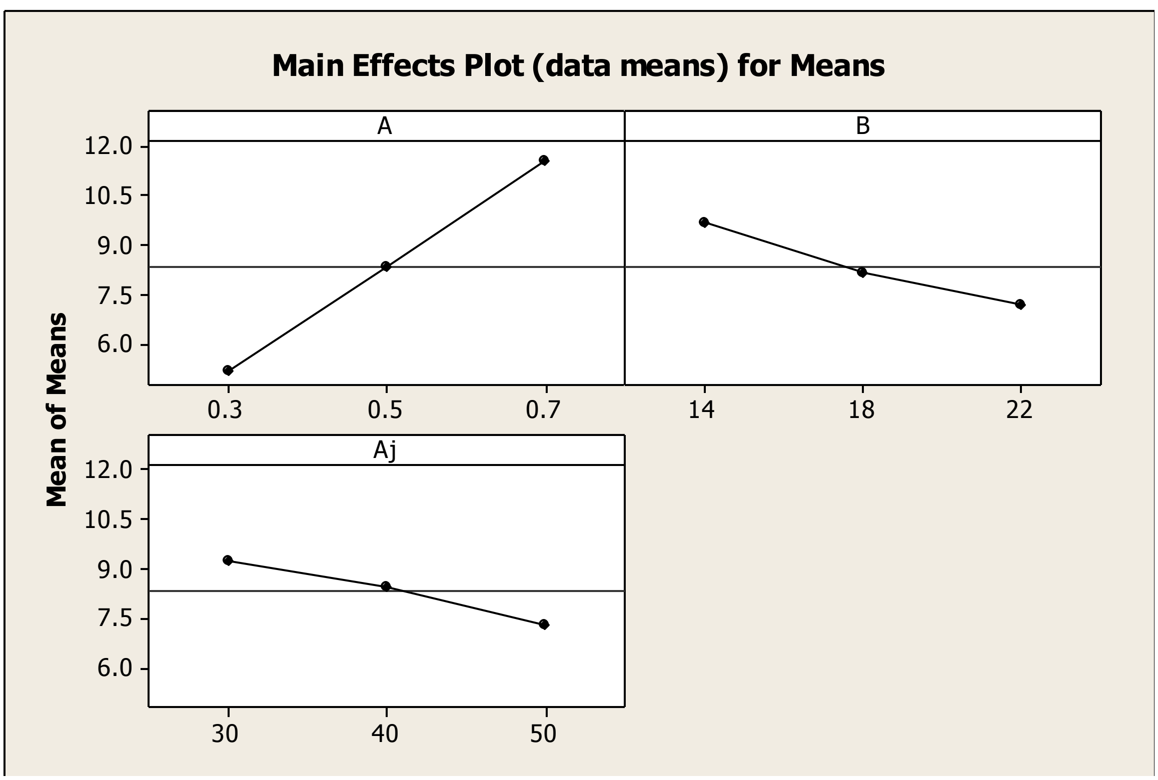


Figure 5.16 Effects of Process Parameters on Cutting Speed (Raw Data)

5.4.1.4.1 Selection of Optimal Levels

It can be seen that the results for the optimal values for D2 steel and zinc coated wire are same as the previous results for D2 steel and high speed brass. The first level of servo reference mean voltage (Aj_1), the first level of time between two pulses (B_1), and the third level of pulse width (A_3) provide maximum value of cutting speed. The S/N data analysis also confirms the results are achieves from raw data analysis.

5.4.2 Effect on Surface roughness

Experiments based on the L18 OA were performed in order to see the influence of process parameters on surface roughness. The surface roughness was measured with Profilometer instrument. The surface roughness raw data and their S/N ratio data for each work piece and tool is given in the tables for each section. The figures in each section for work pieces and wires are plotted based on the raw data and S/N data.

5.4.2.1 Zinc-Coated Wire and D2-Steel

Trial No.	Surface Roughness(μm)		S/N Ratio
	R1	R2	
1	1.95	1.8	-5.46697
2	2.51	2.42	-7.83779
3	2.74	2.6	-8.53321
4	2.1	2.06	-6.36167
5	2.32	2.38	-7.42206
6	2.88	2.84	-9.12753
7	2.36	2.26	-7.27427
8	2.22	2.2	-6.88793
9	2.89	2.9	-9.23298
10	1.84	1.83	-5.27275
11	2.18	2.32	-7.04785
12	2.75	2.77	-8.81824
13	2.02	2	-6.06403
14	2.5	2.45	-7.87195
15	3	3.11	-9.70163
16	1.93	1.82	-5.46376
17	2.46	2.54	-7.95991
18	3.12	3.07	-9.8135

Table 5.28 Experimental Result

ANOVA Tables (5.29 and 5.30) and pooled ANOVA Tables (5.31 and 5.32) are used to investigate the significant effect of each parameter and their interaction in relation to surface roughness.

Time between two pulses and pulse width have significant influence on surface roughness among other parameters. Both ANOVA tables for raw data and S/N data show this result because their P-values are less than 5%.

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
V	1	0.0010	0.0010	0.0010	0.01	0.944
IAL	2	1.4517	1.4517	0.7258	4.21	0.104
A	2	31.1491	31.1491	15.5745	90.32	0.000
B	2	28.7701	28.7701	14.3850	83.44	0.011
Aj	2	0.3983	0.3983	0.1992	1.15	0.402
INJ	2	0.3565	0.3565	0.1783	1.03	0.435
Wb	2	0.8147	0.8147	0.4073	2.36	0.210
Residual Error	4	0.6898	0.6898	0.1724		
Total	17	63.6312				

Table 5.29 Analysis of Variance for SN ratios

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
V	1	0.00109	0.00109	0.00109	0.13	0.735
IAL	2	0.11192	0.11192	0.05596	6.75	0.052
A	2	2.40389	2.40389	1.20194	144.93	0.000
B	2	0.94439	0.94439	0.47221	56.96	0.043
Aj	2	0.03204	0.03204	0.01602	1.93	0.259
INJ	2	0.03312	0.03312	0.01656	2.00	0.250
Wb	2	0.06352	0.06352	0.03176	3.83	0.118
Residual Error	4	0.03317	0.03317	0.00829		
Total	17	3.62314				

Table 5.30 Analysis of Variance for Means

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
A	2	31.1491	31.1491	15.5745	48.02	0.000
B	2	27.3644	27.3644	13.6822	42.19	0.016
A*B	4	0.7929	0.7929	0.1982	0.61	0.665
Residual Error	9	2.9190	2.9190	0.3243		
Total	17	62.2253				

Table 5.31 Pooled Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	2.40389	2.40389	1.20194	47.71	0.000
B	2	2.06942	2.06942	1.03471	41.06	0.019
A*B	4	0.04811	0.04811	0.01203	0.48	0.752
Residual Error	9	0.22675	0.22675	0.02519		
Total	17	4.74817				

Table 5.32 Pooled Analysis of Variance for Means

The following table shows which significant control factor has the most impact on surface roughness. It can be seen that first the pulse width and then the time between two pulses havethe most influence on D2-steel work piece surface roughness that is cut with zinc-coated wire.

Level	A	B
1	1.998	2.443
2	2.375	2.498
3	2.889	2.321
Delta	0.892	0.178
Rank	1	2

Table 5.33 Response Table for Means

It is seen from Figures 5.17 and 5.18 that there is not any interaction between pulse width and time between two pulses on surface roughness since the responses at different levels of process parameters for a given level of parameter value are almost parallel. The results from pooled ANOVA tables comply with the results from the figures.

Figures 5.19 and 5.20 show surface roughness increases when pulse width increase and decreases when time between two pulses increaseas. The discharge energy increases with the pulse width increase and larger discharge energy produces a larger crater. Then larger crater make a larger surface roughness value. The number of discharges increases while time between two pulses decreases. Then it causes poor surface accuracy.

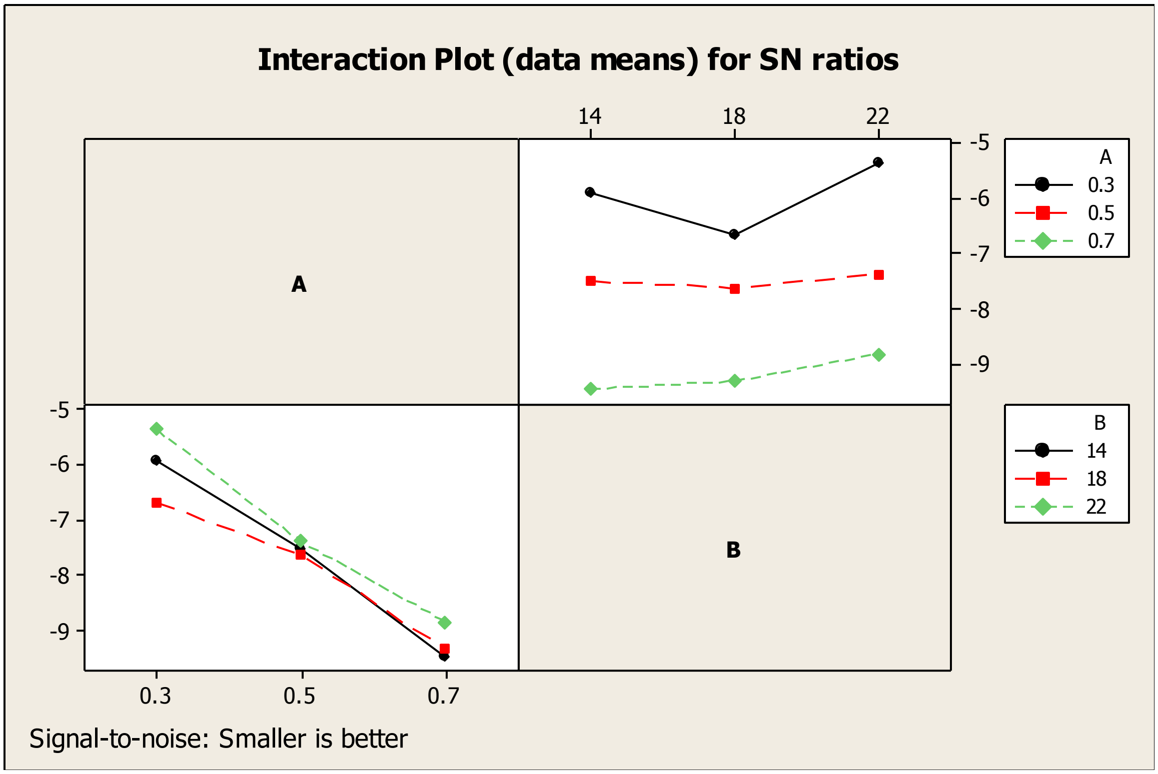


Figure 5.17 Effects of Process Parameters Interaction on Cutting Speed (S/N Data)

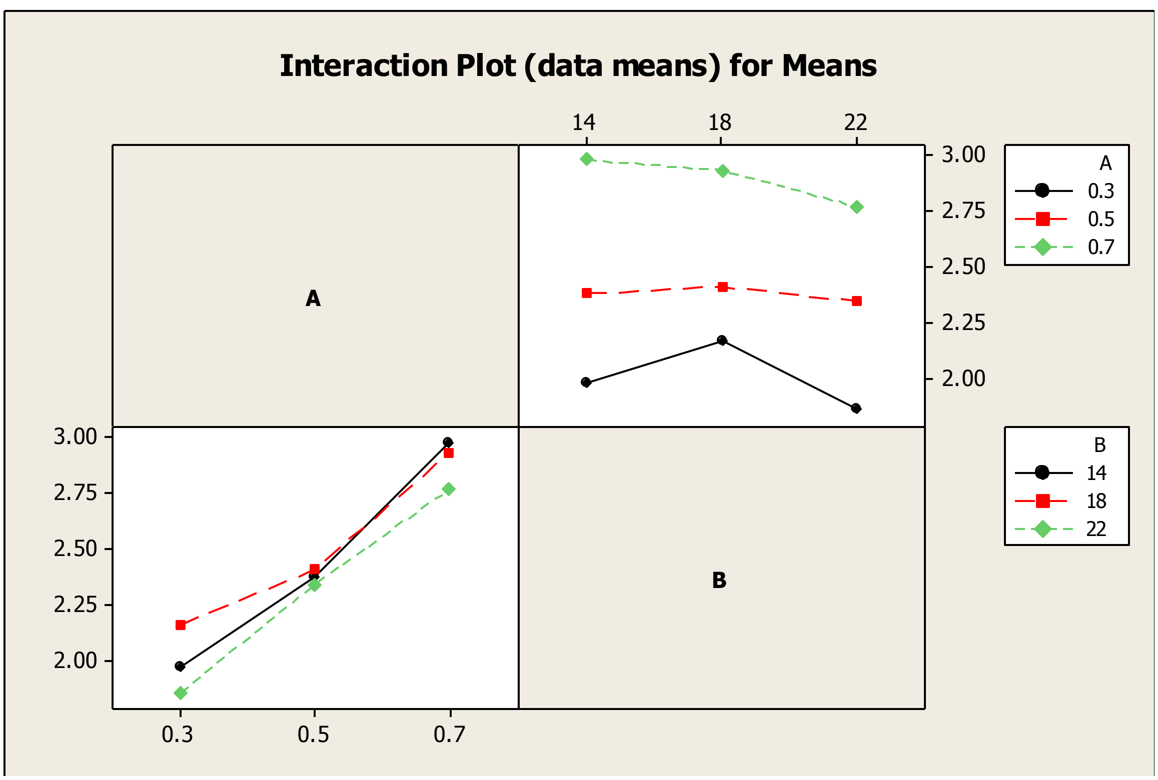


Figure 5.18 Effects of Process Parameters Interaction on Cutting Speed (Raw Data)

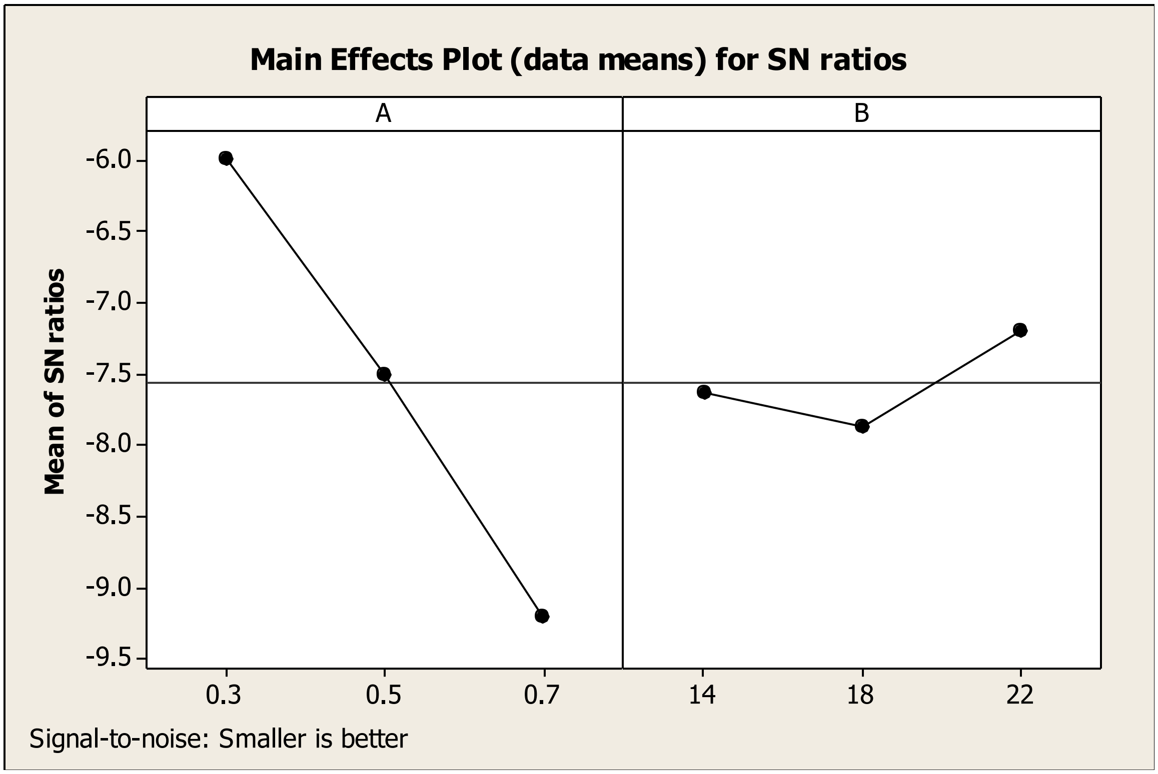


Figure 5.19 Effects of Process Parameters on Cutting Speed (Raw Data)

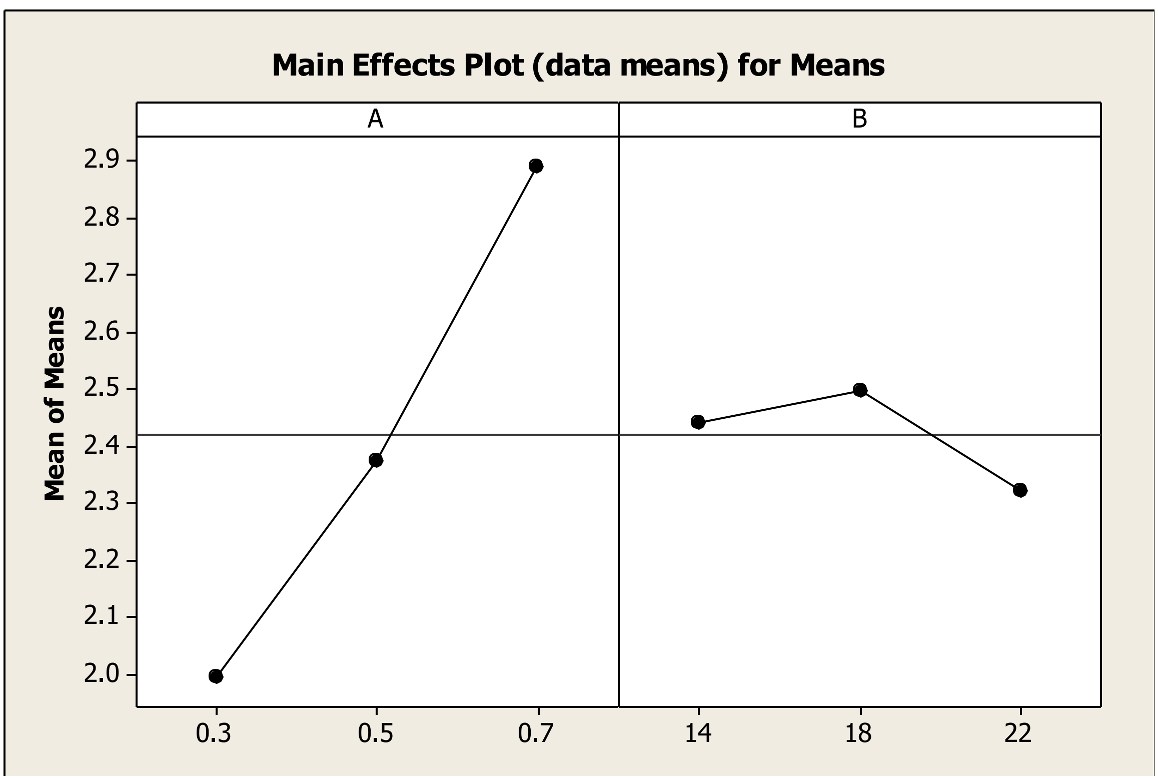


Figure 5.20 Effects of Process Parameters on Cutting Speed (Raw Data)

5.4.2.1.1 Selection of Optimal Values

The surface roughness is the ‘’lower the better’’ type quality characteristic. In Figure 5.29, it can be seen that the first level of pulse width (A_1) and the third level of time between two pulses (B_3) result in the minimum value of surface roughness. The S/N ratio analysis (Figure 5.28) also suggests the same levels of the variables (A_1, B_3) as the best levels for the minimum SR in WEDM process.

5.4.2.2 High Speed Brass and D2-Steel

Trial No.	Surface Roughness(μm)		S/N Ratio
	R1	R2	
1	2.6	2.84	-8.69982
2	3.17	3.2	-10.0623
3	3.3	3.34	-10.4229
4	2.88	2.8	-9.06723
5	2.86	2.85	-9.11214
6	3.29	3.31	-10.3703
7	2.83	2.73	-8.8823
8	2.71	2.66	-8.57926
9	3.48	3.49	-10.8441
10	2.29	2.31	-7.23464
11	3.11	3.21	-9.99483
12	3.27	3.16	-10.1449
13	2.44	2.32	-7.5343
14	3.15	3.19	-10.0214
15	3.7	3.78	-11.4579
16	2.41	2.4	-7.62232
17	3.18	3.15	-10.0076
18	3.82	3.78	-11.5958

Table 5.34 Experimental Results

Based on the ANOVA Tables 5.35 and 5.36 for D2 steel work piece and high speed brass, only pulse width and time between two pulses are significant process parameters. These results are the same as the last section results for D2 steel and zinc coated wire.

In addition, pooled ANOVA Tables (5.37 and 5.38) show time between two pulses and pulse width do not have any interaction with each other because their P-value is more than 0.05.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	1	0.0101	0.0101	0.0101	0.03	0.861
IAL	2	0.1085	0.1085	0.0543	0.19	0.836
A	2	20.8692	20.8692	10.4346	35.99	0.003
B	2	10.9408	10.9408	5.4704	18.87	0.035
Aj	2	1.6400	1.6400	0.8200	2.83	0.172
INJ	2	1.0334	1.0334	0.5167	1.78	0.280
Wb	2	0.2057	0.2057	0.1028	0.35	0.721
Residual Error	4	1.1596	1.1596	0.2899		
Total	17	35.9673				

Table 5.35 Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	1	0.00151	0.00151	0.00151	0.05	0.834
IAL	2	0.01810	0.01810	0.00905	0.30	0.758
A	2	2.46227	2.46227	1.23113	40.52	0.002
B	2	0.91864	0.91864	0.45934	15.12	0.049
Aj	2	0.17164	0.17164	0.08582	2.82	0.172
INJ	2	0.14620	0.14620	0.07310	2.41	0.206
Wb	2	0.03210	0.03210	0.01605	0.53	0.626
Residual Error	4	0.12153	0.12153	0.03038		
Total	17	3.87199				

Table 5.36 Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	20.8692	20.8692	10.4346	24.81	0.000
B	2	11.2357	11.2357	5.6178	13.36	0.031
A*B	4	0.3724	0.3724	0.0931	0.22	0.920
Residual Error	9	3.7848	3.7848	0.4205		
Total	17	36.2621				

Table 5.37 Pooled Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	2.46227	2.46227	1.23113	23.64	0.000
B	2	2.18589	2.18589	1.09294	20.99	0.010
A*B	4	0.02247	0.02247	0.00562	0.11	0.977
Residual Error	9	0.46861	0.46861	0.05207		
Total	17	5.13924				

Table 5.38 Pooled Analysis of Variance for Means

It is noticed from the following table that pulse width has the maximum impact on the surface roughness among other process parameters followed by time between two pulses.

Level	A	B
1	2.571	3.185
2	3.037	3.036
3	3.477	2.863
Delta	0.906	0.322
Rank	1	2

Table 5.39 Response Table for Means

Figures 5.21 and 5.22 show there is no interaction between pulse width and time between two pulses in affecting in the surface roughness since the responses at different levels of process parameters for a given level of parameter value are almost parallel. Pooled ANOVA tables also confirm the results from the Figures.

In cutting D2 Steel with high speed brass all results and plots based on the raw data and S/N data analysis are same as each other. As it can be seen in Figures 5.23 and 5.24, surface roughness increases by increase in pulse width and decreases by increase in time between two pulses. Pulse width improvement makesmore discharge energy and larger discharge energy produces a larger crater which causes a larger surface roughness value. On the other hand, higher surface accuracy is obtained due to increase in the number of discharges when time between two pulses decreases.

5.4.2.2.1 Selection of Optimal Values

The S/N ratio raw data analysis indicates the combination of the first level of pulse width (A_1) and the third level of time between two pulses (B_3) gives the lowest value of surface roughness that is the optimal value.

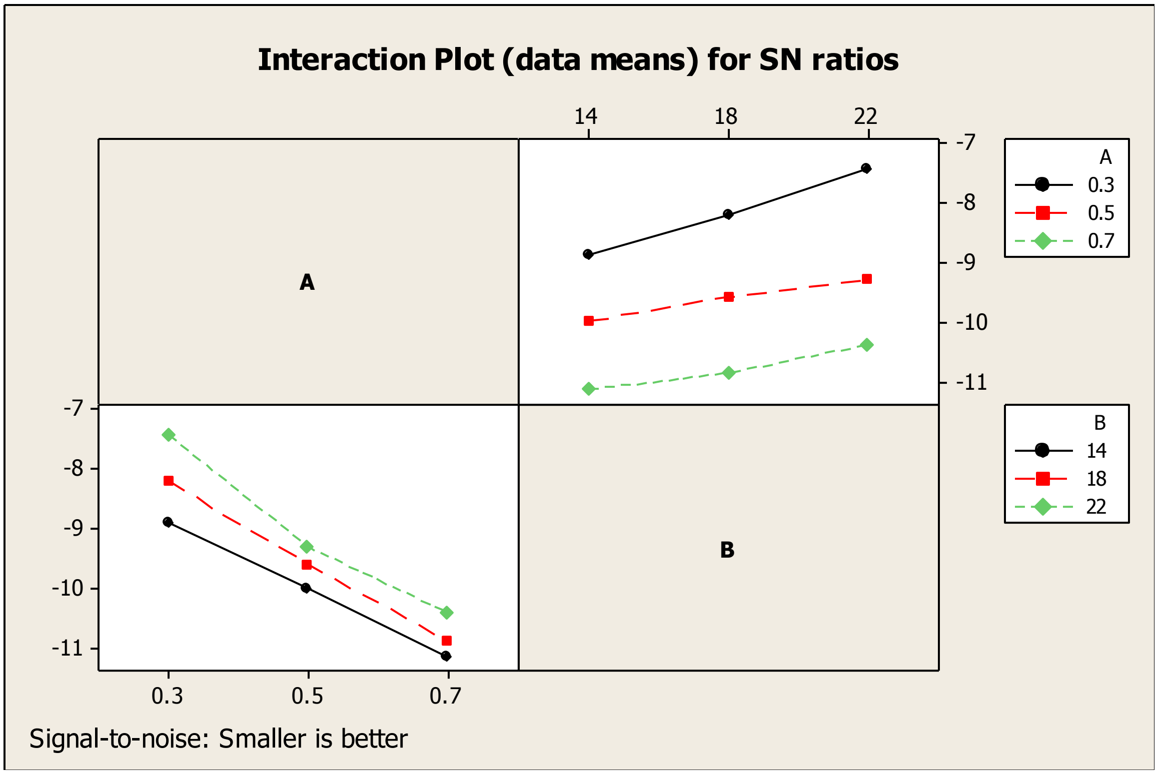


Figure 5.21 Effects of Process Parameters Interaction on Cutting Speed (S/N Data)

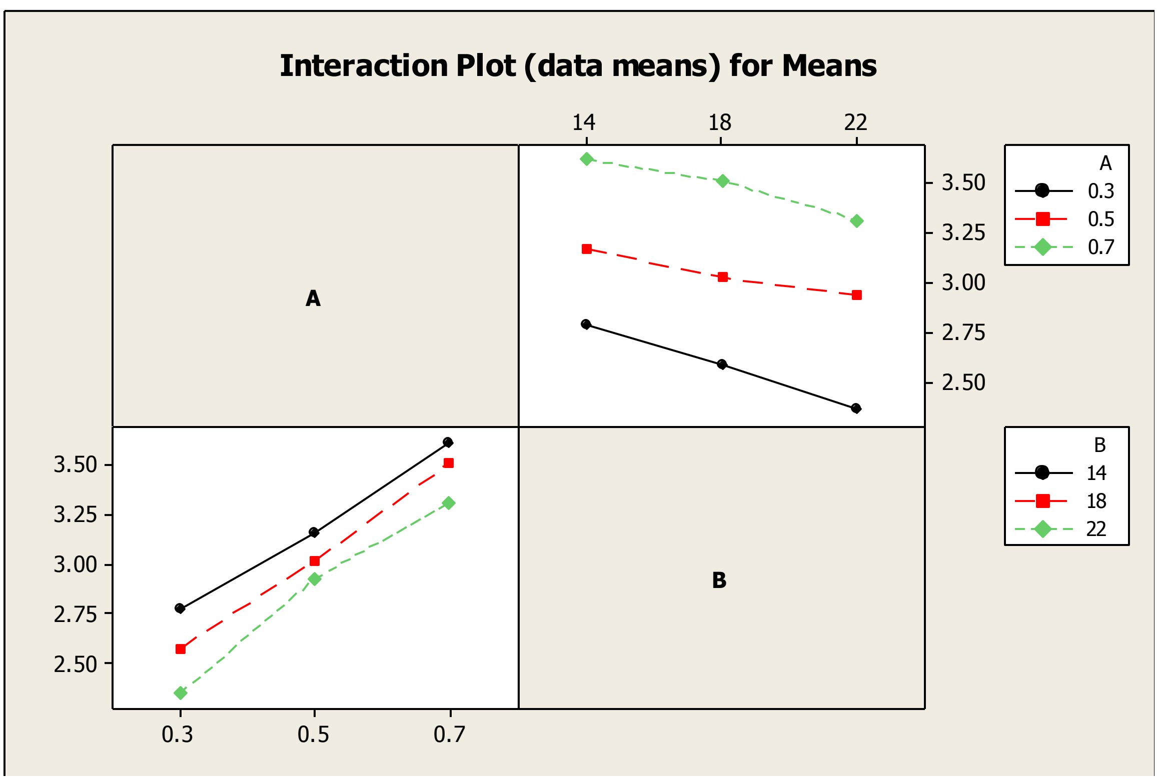


Figure 5.22 Effects of Process Parameters Interaction on Cutting Speed (Raw Data)

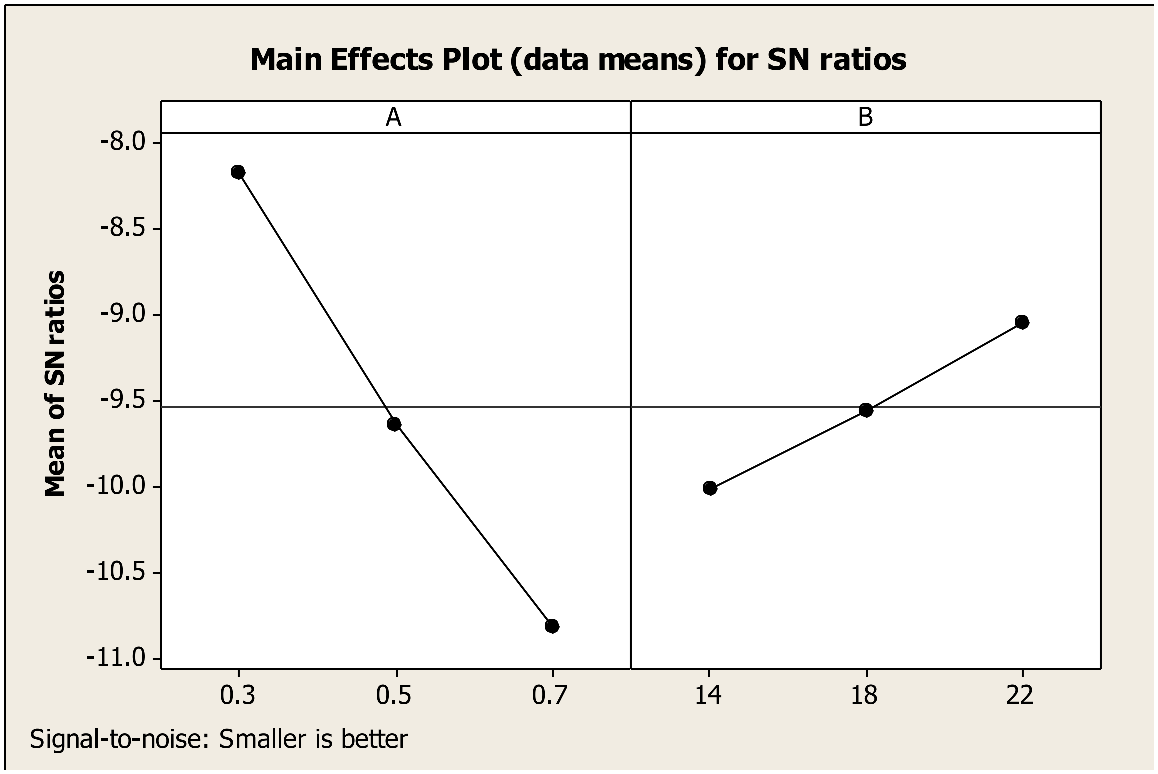


Figure 5.23 Effects of Process Parameters on Cutting Speed (S/N Data)

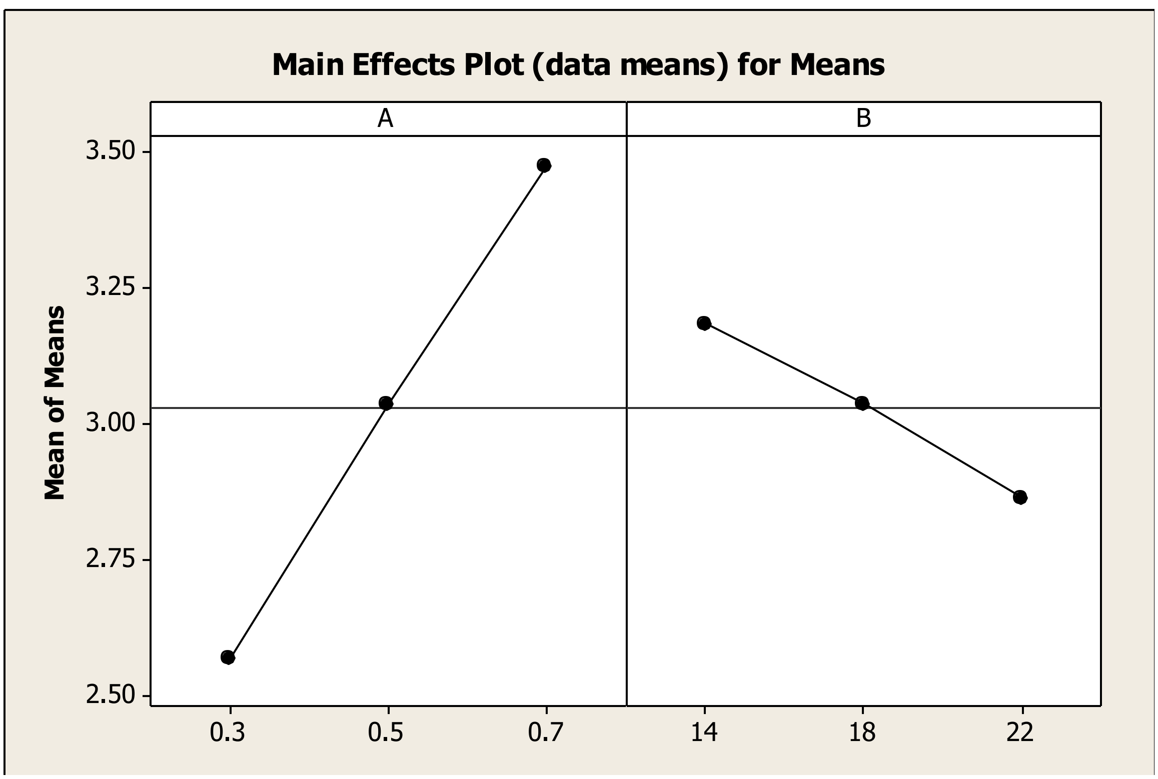


Figure 5.24 Effects of Process Parameters on Cutting Speed (Raw Data)

5.4.2.3 Zinc- Coated Wire and Titanium

Trial No.	Surface Roughness(μm)		S/N Ratio
	R1	R2	
1	1.86	1.8	-5.25019
2	2.47	2.5	-7.90669
3	2.51	2.44	-7.87237
4	1.9	1.93	-5.64364
5	2.3	2.23	-7.1024
6	2.62	2.57	-8.28315
7	2.37	2.4	-7.54994
8	2.2	2.16	-6.7695
9	2.98	2.98	-9.48433
10	1.78	1.81	-5.08159
11	2.05	2	-6.12916
12	2.67	2.58	-8.38386
13	2	2.11	-6.25935
14	2.17	2.15	-6.68917
15	2.79	2.7	-8.77201
16	2.1	2.14	-6.5271
17	2.44	2.4	-7.6766
18	2.61	2.58	-8.28289

Table 5.40 Experimental Results

The average values of surface roughness for each parameter at their levels for raw data and S/N data were analyzed and ANOVA tables (5.41 and 5.42) were performed based on them. In WEDM of titanium with zinc-coated wire pulse width, wire tension and peak current are the significant parameters for surface roughness. Other parameters such as voltage, time between two pulses, servo mean references and injection pressure do not have any influence on surface roughness.

The P-value of pooled ANOVA Tables 5.43 and 5.44 shows there is an interaction between peak current and pulse width but wire tension does not have any interactionwith pulse width and peak current.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	1	0.2359	0.2359	0.23586	0.63	0.471
IAL	2	13.1514	13.1514	6.56768	17.67	0.012
A	2	18.3961	18.3961	9.19806	24.71	0.006
B	2	1.5315	1.5315	0.76575	2.06	0.243
Aj	2	0.2918	0.2918	0.14591	0.39	0.699
INJ	2	0.1519	0.1519	0.07595	0.20	0.823
Wb	2	9.7619	9.7619	4.87582	13.10	0.023
Residual Error	4	1.4890	1.4890	0.37225		
Total	17	45.0095				

Table 5.41 Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	1	0.01805	0.01805	0.018050	0.74	0.439
IAL	2	1.15981	1.15981	0.579970	23.66	0.012
A	2	1.30760	1.30760	0.653801	26.67	0.005
B	2	0.09835	0.09835	0.049176	2.01	0.249
Aj	2	0.02204	0.02204	0.011022	0.45	0.667
INJ	2	0.00855	0.00855	0.004276	0.17	0.846
Wb	2	0.85401	0.85401	0.402254	16.41	0.020
Residual Error	4	0.09805	0.09805	0.024513		
Total	17	3.56646				

Table 5.42 Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
IAL	2	2.731	2.731	1.3657	9.03	0.012
A	2	18.396	18.396	9.1981	60.81	0.000
Wb	2	1.562	2.717	1.3583	8.98	0.012
IAL*A	4	2.641	2.641	0.6603	4.37	0.044
Residual Error	7	1.059	1.059	0.1513		
Total	17	26.389				

Table 5.43 Pooled Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
IAL	2	0.17950	0.17950	0.08975	8.34	0.014
A	2	1.30760	1.30760	0.65380	60.76	0.000
Wb	2	0.11837	0.20693	0.10346	9.62	0.010
IAL*A	4	0.16973	0.16973	0.04243	3.94	0.048
Residual Error	7	0.07532	0.07532	0.01076		
Total	17	1.85053				

Table 5.44 Pooled Analysis of Variance for Means

The ranks indicate the relative importance of each factor to the response. The ranks and the delta values for various parameters show that pulse width has the greatest effect on surface roughness and is followed by peak current and wire tension in that order.

Level	IAL	A	Wb
1	2.206	2.017	2.330
2	2.289	2.256	2.404
3	2.447	2.669	2.208
Delta	0.241	0.653	0.197
Rank	2	1	3

Table 5.45 Response Table for Means

It is noticed from Figures 5.25 and 5.26 that there is a slight interaction between pulse width and peak current while there is not any interaction between all the other process parameters in affecting the surface roughness. Peak current and pulse width converge to each other and cross each other in next steps.

It is observed from Figures 5.27 and 5.28 surface roughness value increases when pulse width and peak current increase. The discharge energy increases with the pulse on time and peak current. The larger discharge energy produces a larger crater, causing a larger surface roughness value on the work piece. On the other hand, increase in wire tension causes reduction in surface roughness. Therefore, surface roughness quality of the machined part is improved due to increase of wire tension because of reduction in its vibration.

5.4.2.3.1 Selection of Optimal Values

The S/N ratio and raw data analysis indicate the combination of the first level of pulse width (A_1), the firstlevel of peak current (IAL_3) and the third level of wire tension (Wb_3) give the lowest value of surface roughness that is the optimal value.

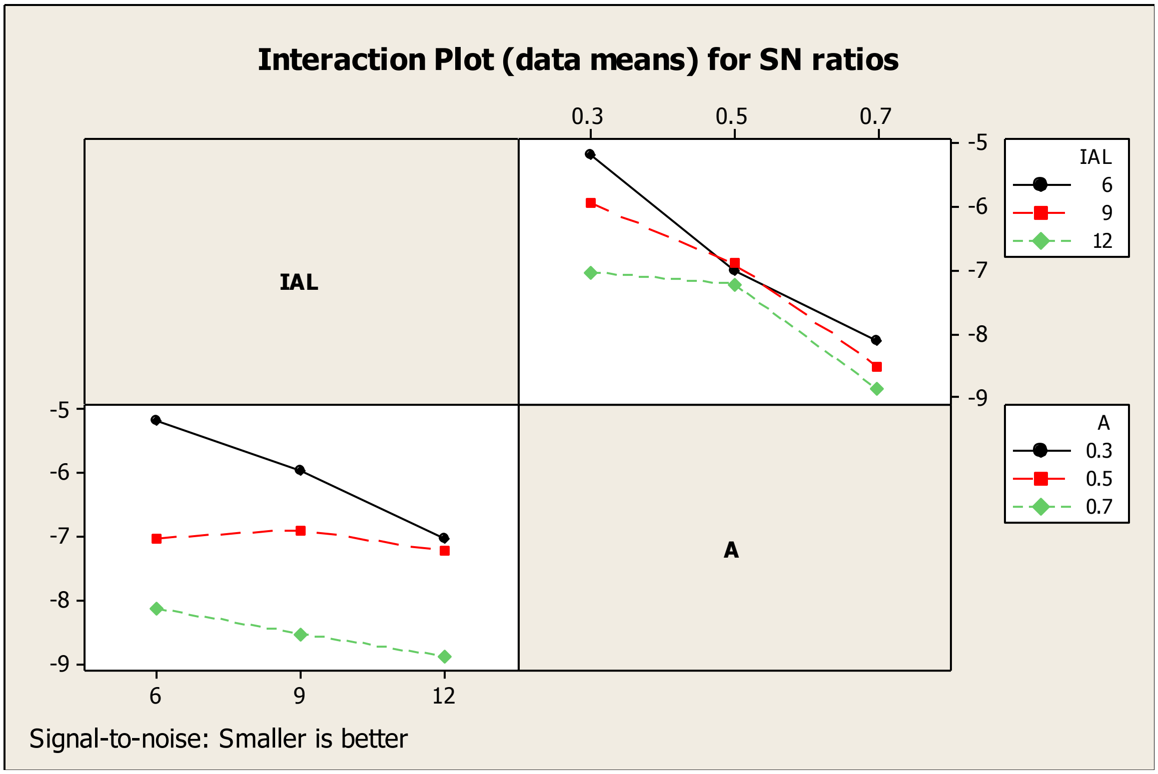


Figure 5.25 Effects of Process Parameters Interaction on Cutting Speed (S/N Data)

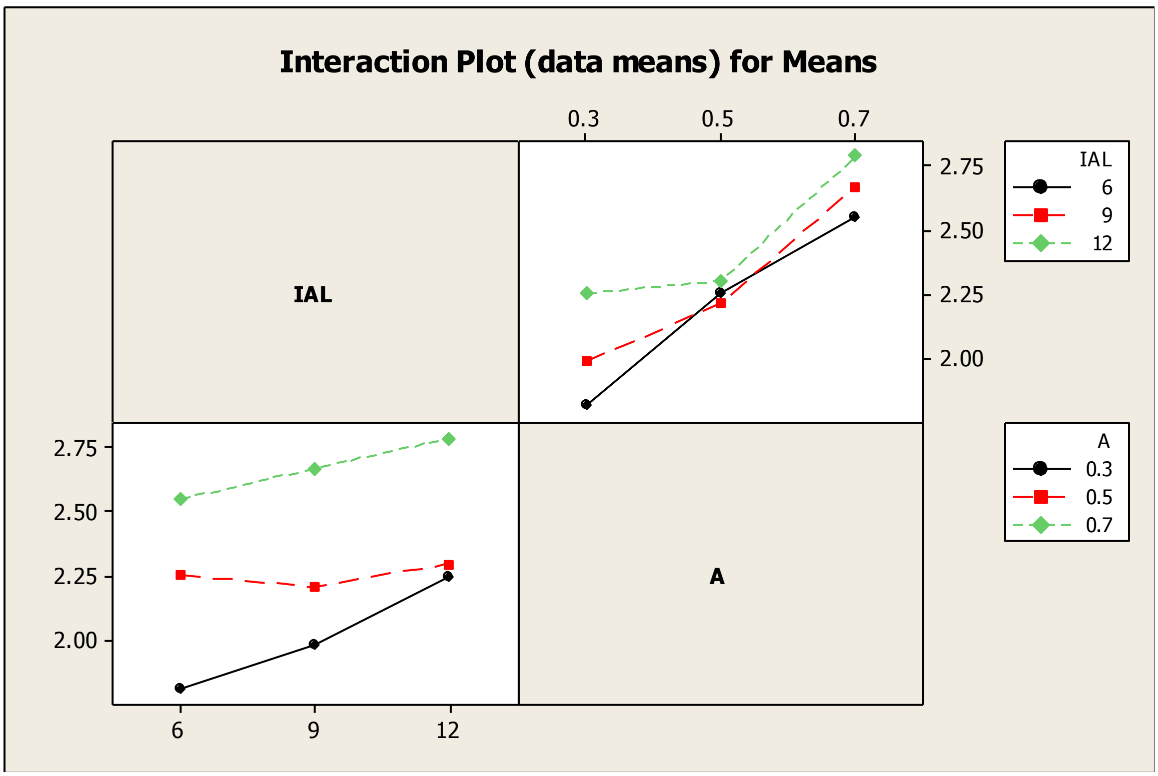


Figure 5.26 Effects of Process Parameters Interaction on Cutting Speed (Raw Data)

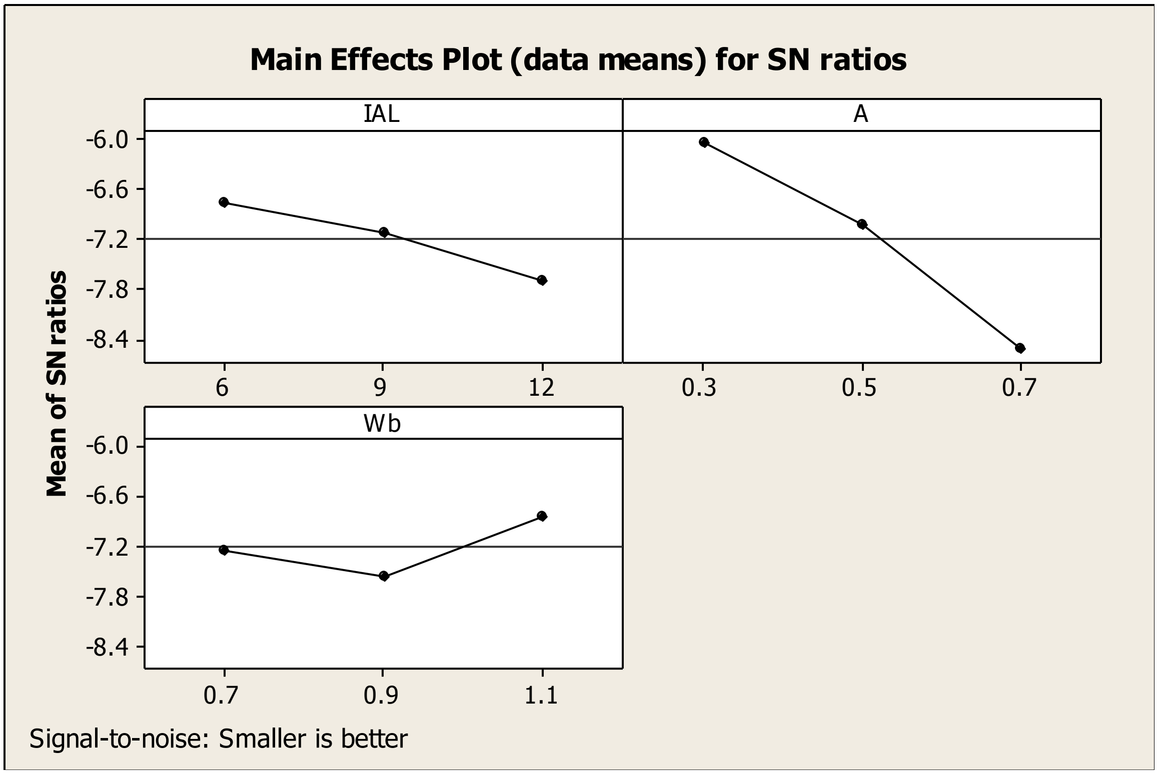


Figure 5.27 Effects of Process Parameters on Cutting Speed (S/N Data)

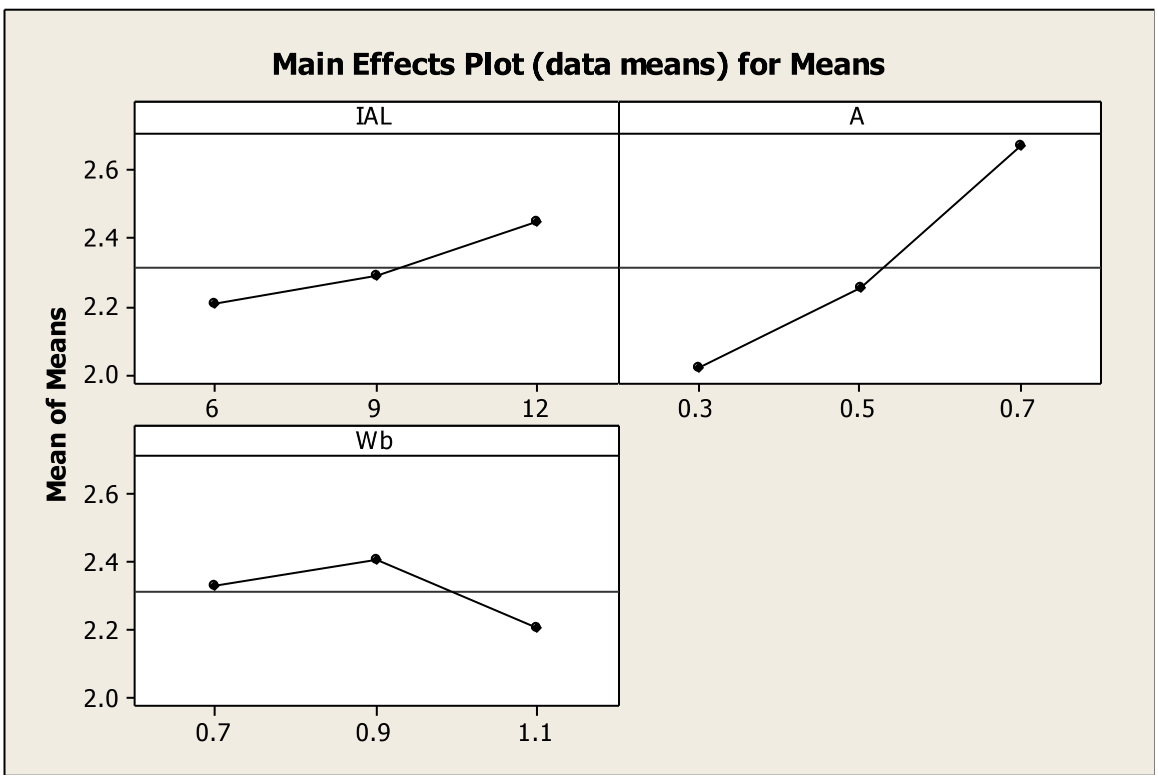


Figure 5.28 Effects of Process Parameters on Cutting Speed (Raw Data)

5.4.2.4 High-Speed Brass and Titanium

Trial No.	Surface Roughness(μm)		S/N Ratio
	R1	R2	
1	2.43	2.45	-7.74787
2	2.56	2.6	-8.23266
3	2.64	2.61	-8.38273
4	2.42	2.48	-7.78397
5	2.44	2.5	-7.85458
6	3.04	3	-9.60033
7	2.79	2.8	-8.92765
8	2.52	2.48	-7.95908
9	3.18	3.22	-10.1032
10	2.16	2.14	-6.64886
11	2.55	2.5	-8.04565
12	3.16	3.17	-10.0075
13	2.76	2.8	-8.88112
14	2.74	2.8	-8.8501
15	3.19	3.12	-9.98052
16	2.61	2.64	-8.38273
17	2.66	2.69	-8.54661
18	2.76	2.73	-8.77098

Table 5.46 Experimental Results

The purpose of the analysis is to determine the factors and their interactions that have strong effects on the machining performance. It is concluded from the ANOVA Tables 5.47 and 5.48 that peak current, pulse width and wire tension can be treated as significant factors whereas voltage, time between two pulses, injection pressure and servo mean references voltage are less significant factors for minimization of surface roughness.Significant process parameters on surface roughness for titanium machining with wires type, high speed brass and zinc coated are the same.

Based on the pooled ANOVA Tables 5.49 and 5.50, interaction between peak current and pulse width does not have significant effects on surface roughness. Their P-value is more than 0.05. These results are obtained based on the raw data and S/N data analysis.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	1	0.1287	0.1287	0.1287	0.18	0.697
IAL	2	24.4906	24.4906	13.2453	18.07	0.032
A	2	65.7061	65.7061	32.8532	44.82	0.08
B	2	0.7793	0.7793	0.3896	0.53	0.624
Aj	2	0.3452	0.3452	0.1726	0.24	0.800
INJ	2	0.4613	0.4613	0.2306	0.31	0.747
Wb	2	14.0442	14.0442	7.0221	9.58	0.046
Residual Error	4	2.9322	2.9322	0.7330		
Total	17	108.8876				

Table 5.47 Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
V	1	0.01445	0.01445	0.01445	0.21	0.670
IAL	2	2.19236	2.19236	1.09616	16.00	0.038
A	2	4.82854	4.82854	2.41427	35.24	0.016
B	2	0.07179	0.07179	0.03589	0.52	0.628
Aj	2	0.02884	0.02884	0.01442	0.21	0.819
INJ	2	0.03930	0.03930	0.01965	0.29	0.765
Wb	2	1.05627	1.05627	0.52813	7.71	0.045
Residual Error	4	0.27405	0.27405	0.06851		
Total	17	8.5056				

Table 5.48 Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
IAL	2	5.8307	5.830	2.9153	9.59	0.014
A	2	7.0643	7.064	3.5321	11.62	0.006
Wb	2	3.4108	3.410	1.7054	5.61	0.040
IAL*A	4	2.5188	2.519	0.6297	2.07	0.188
Residual Error	7	2.1278	2.128	0.3040		
Total	17	20.9524				

Table 5.49 Pooled Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
IAL	2	0.59581	0.5958	0.29793	10.38	0.016
A	2	0.71774	0.7177	0.35887	12.46	0.005
Wb	2	0.34382	0.3438	0.17193	5.99	0.047
IAL*A	4	0.22689	0.2269	0.05672	1.97	0.204
Residual Error	7	0.20154	0.2015	0.02879		
Total	17	2.0858				

Table 5.50 Pooled Analysis of Variance for Means

The rank and the delta values in the following table show pulse width has the maximum impact on surface roughness as similar as last section for titanium and zinc coated wire. Additionally, peak current and wire tension are in the second and third levels of importance respectively.

Level	IAL	A	Wb
1	2.581	2.540	2.778
2	2.774	2.587	2.729
3	2.757	2.985	2.604
Delta	0.193	0.445	0.174
Rank	2	1	3

Table 5.51 Response Table for Means

It is noticed from Figures 5.29 and 5.30 that there is not any interaction between pulse width and peak current since the response at different levels of process parameters are almost parallel or are a little close first but then become divergent.

It is observed from Figures 5.31 and 5.32 that surface roughness value increases when pulse width and peak current increase because the discharge energy increases. The larger discharge energy produces a larger crater, causing a larger surface roughness value on the work piece. On the other hand, increase in wire tension causes reduction in surface roughness. Therefore, surface roughness quality of the machined part is improved since the increase of wire tension reduces its vibration.

5.4.2.4.1 Selection of Optimal Values

Analysis of the results of S/N ratio and raw data leads to the conclusion that the factors pulse width at first level (A_1), peak current at first level (IAL_3) and wire tension at third level (Wb_3) can be set for minimization of surface roughness.

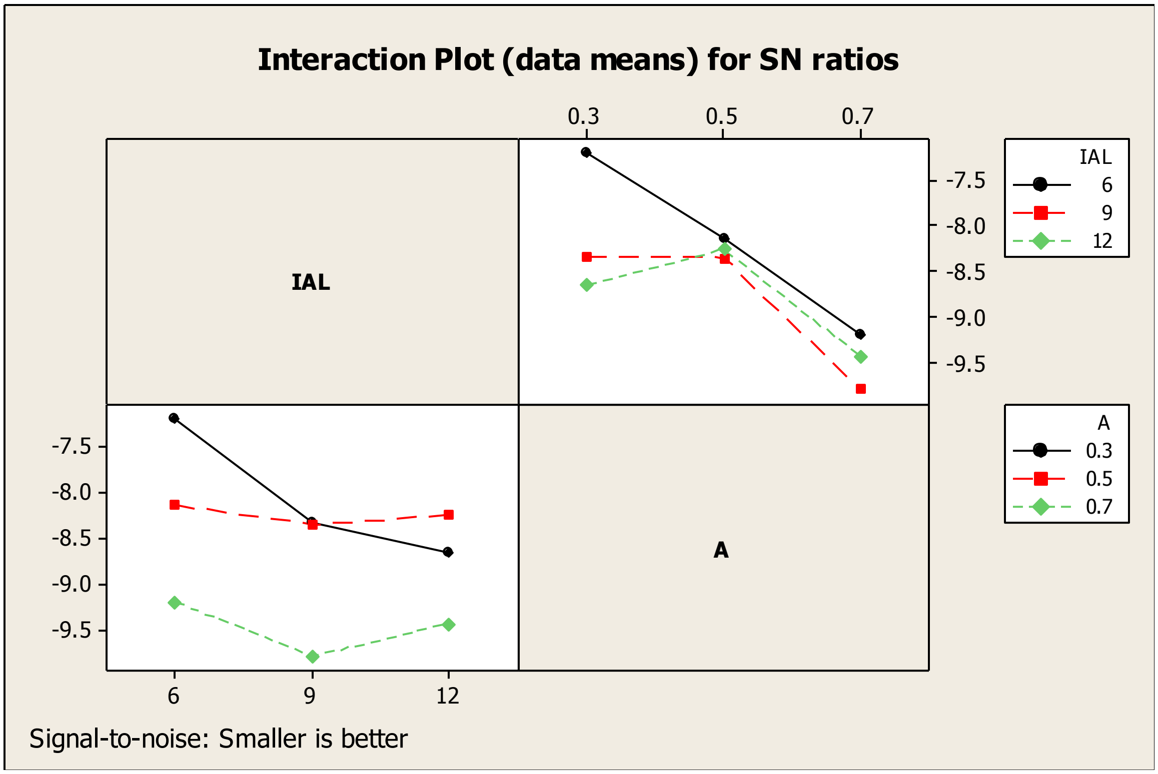


Figure 5.29 Effects of Process Parameters Interaction on Cutting Speed (S/N Data)

Figure 5.30 Effects of Process Parameters Interaction on Cutting Speed (Raw Data)

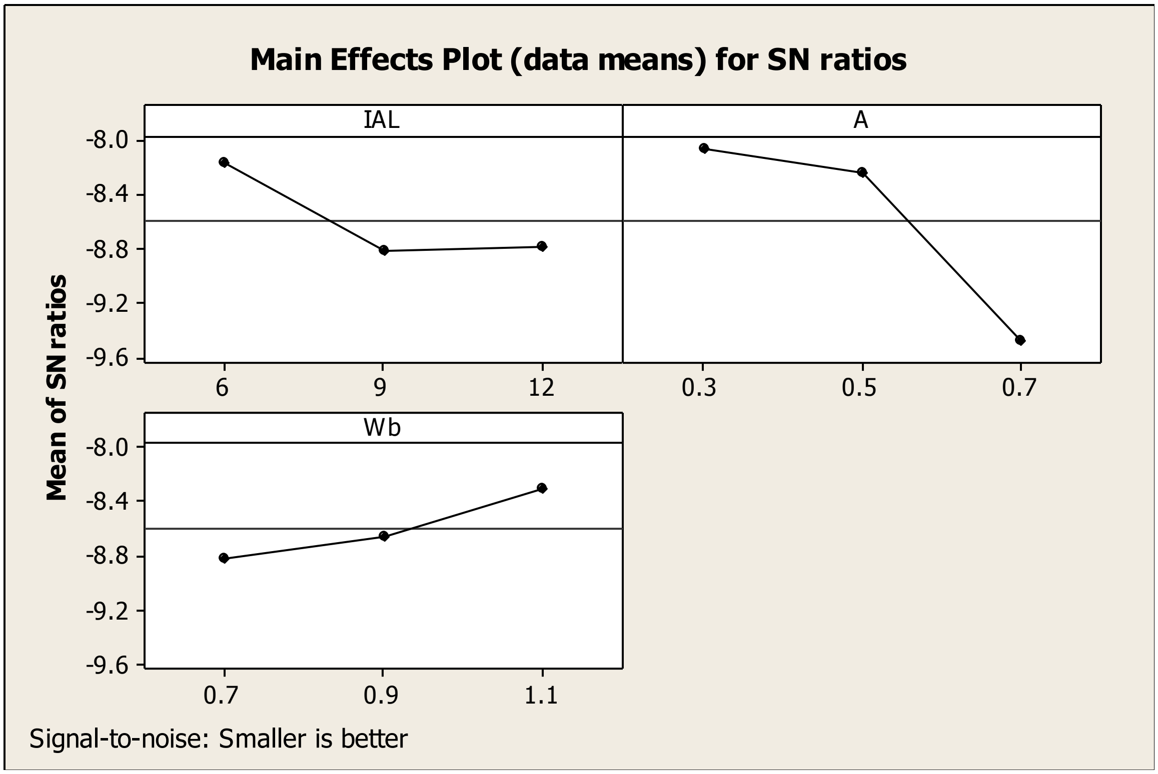


Figure 5.31 Effects of Process Parameters on Cutting Speed (S/N Data)

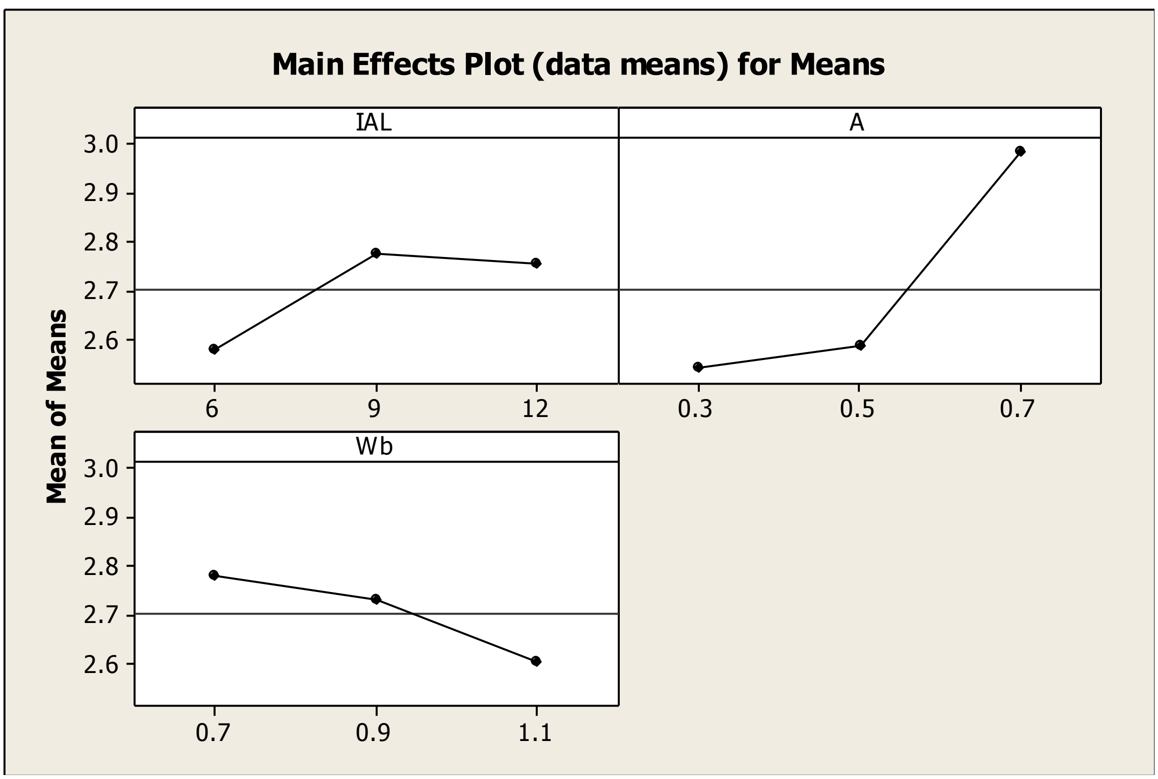
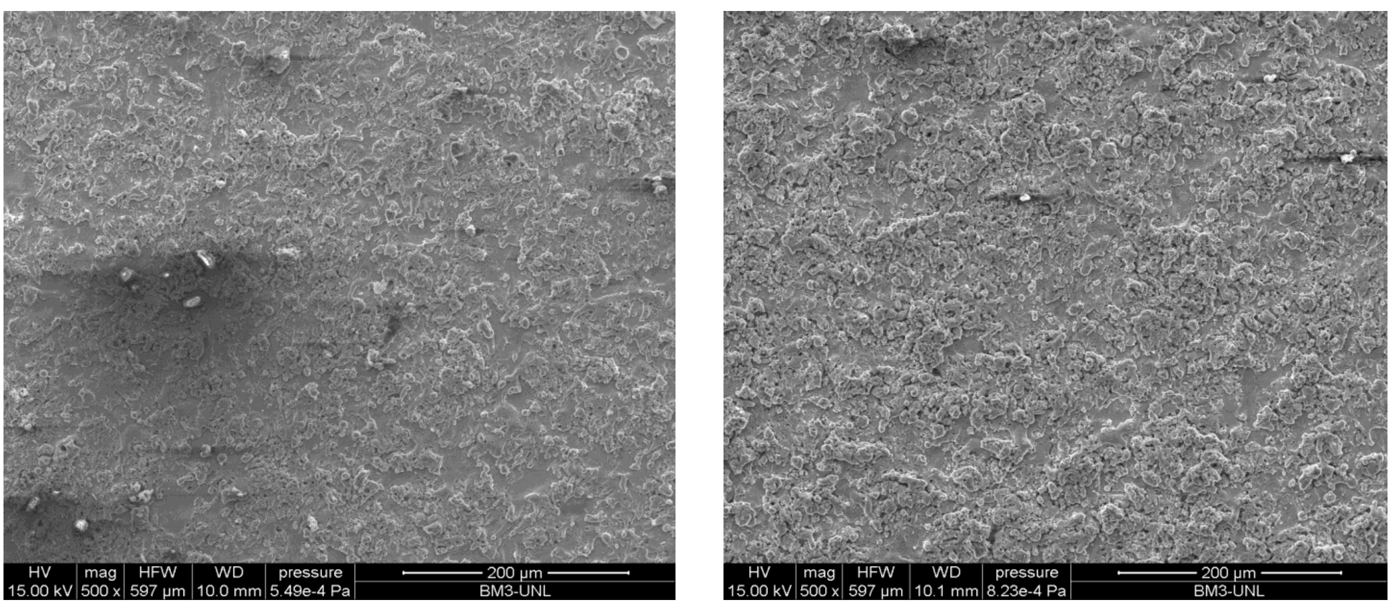


Figure 5.32 Effects of Process Parameters on Cutting Speed (Raw Data)

5.5 SEM Micrographs of WEDM Surface

Scanning Electron Microscopy (SEM) views of the WEDMed surfaces were taken in order to compare the effect of different wire types on machining of various work piece materials by analyzing surface integrity and characteristics. The surface integrity consists of roughness, size of craters and depth of a recast layer and heat affected zone that are investigated in this section for titanium and D2 steel.

Figure 5.33 shows the surface of D2 steel work pieces which are machined with different wire materials but under the same conditions and with the same parameters set of Wire EDM process. In addition, their SEM images have been taken with the same magnification. Figure 5.33 (a) belongs to D2 steel which is processed by zinc coated wire. High speed brass is used to process the D2 steel that is showed in Figure 5.33 (b).

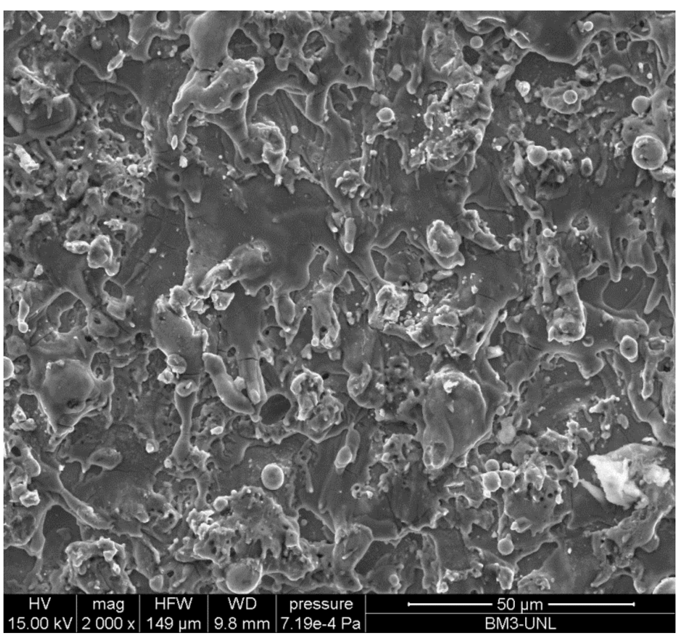


(a) **(b)**

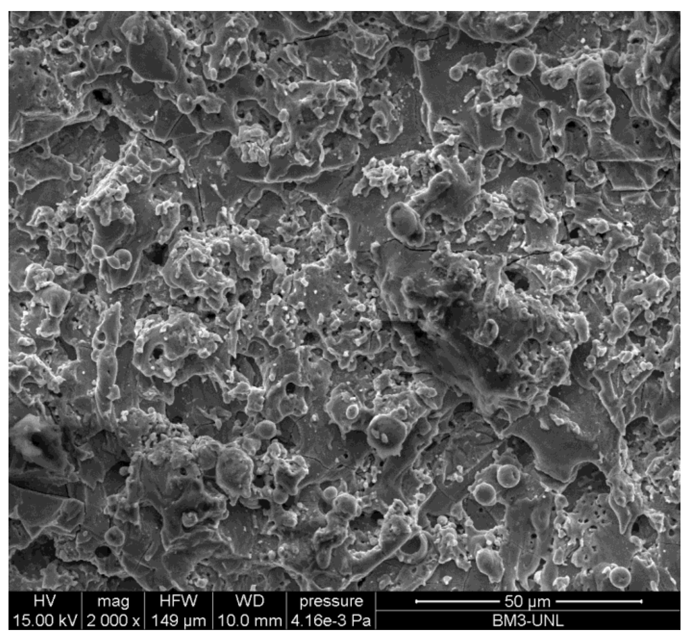
Figure 5.33 SEM Micrograph of D2 Steel

From the examination of the surface characteristics that are showed in Figure 5.34, it is observed that high speed brass wire caused a poor surface finish. Figures 5.34 (a,b) is smoother than the work piece produced by high speed brass in Figures 5.34 (c,d). Also, it can be seen zinc coated wire produces less ridge on the work piece surface. Poor quality surfaces by uncoated wire results from the non-uniform thermal load on the samples. This non-uniform thermal load is due to non-uniform spark formation and inefficient flushing characteristics. Improper flushing can also cause arc formation, which can further damage the surface.

Figure 5.34 shows a comparison between the surface of titanium machined under the same conditions and processing parameter values by high speed brass wire and zinc coated wire. It is evident that the sample is produced with uncoated wire in Figures 5.34.(c,d) has more melted drops, globules of debris, craters and cracks. Due to low melting temperature and high heat conductivity the zinc coated wire produces better surface quality for titanium and D2 steel materials.



(a)



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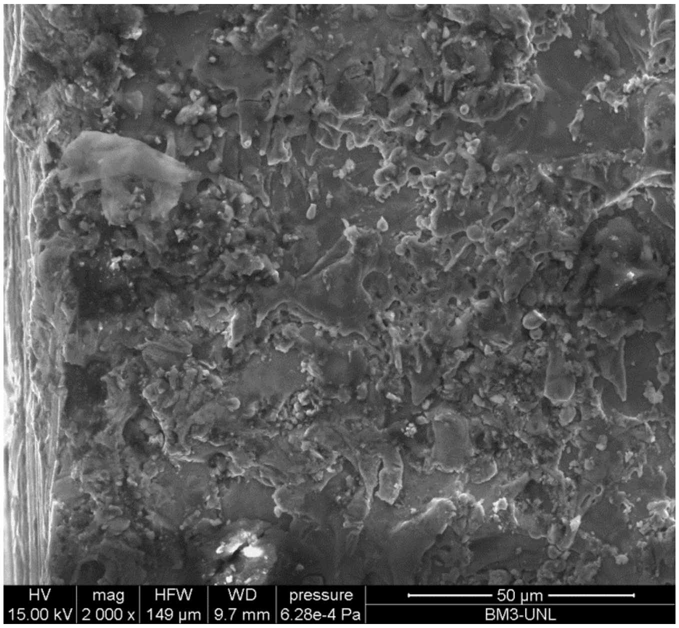
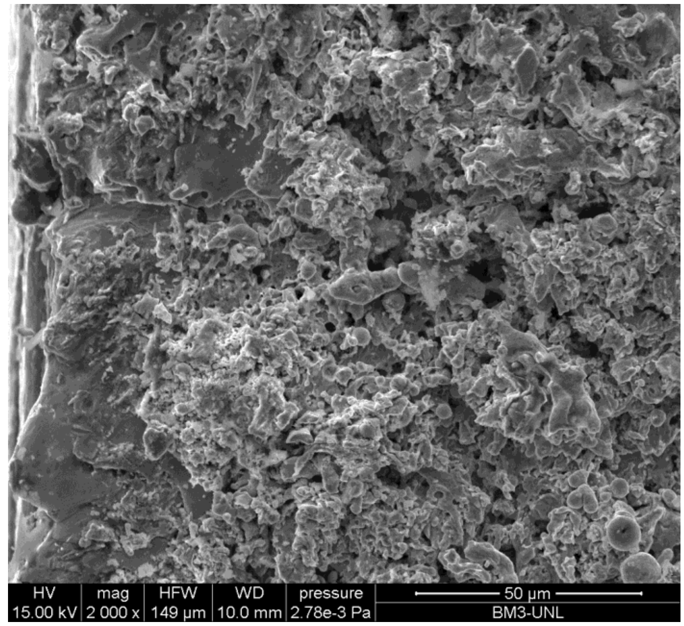


(b)



(d)

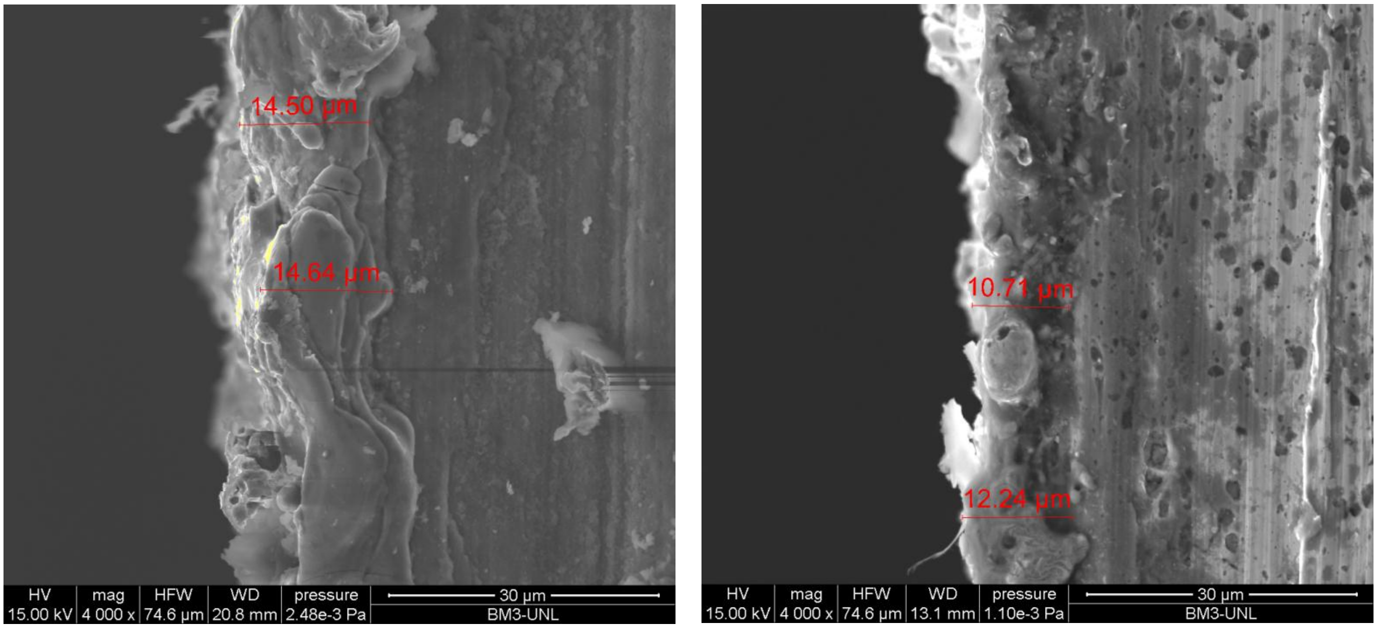
Figure 5.34 SEM Micrograph of Machined Work Piece with High-Speed Brass Wire and Zinc-Coated Wire

Indeed, the damaged layers consist of 3 layers, namely white layer, recast layer and heat-affected zone. The recast layer is defined as the material melted by electrical sparks and not removed by flushing.

Same conclusions can be made when using D2 steel work piece and different electrodes materials according to Figures 5.35 (a,b). The heat-affected zone was found to be limited in its thickness and could not be distinguished easily. Therefore, the depth of damaged layer reported here was measured from the extreme surface to the end of recast zone.

As shown in Figure 5.35 the thickness of damaged layer of D2 steel machined with zinc coated wire (5.35(b)) is lower than the other one produced by high speed brass wire. Zinc coated wire has good electrical conductivity that helps the wire transfer energy to work piece efficiently.

Then, it leads to apply low heat energy to the specimens' surface and decrease the damaged layer formed.



(a) **(b)**

Figure 5.35 SEM Micrograph of D2 Steel

Figures 5.36 (a,b) show the SEM images of D2 steel machined by zinc coated wire and Figures5.36 (c.d) belongs to titanium work piece machined by zinc coated wire. All parameters sets and process conditions are the same for producing these samples except the work pieces materials. It is obvious that the surface of D2 steel is softer than titanium surface finish. The melted drops, globules of debris and pockmarks are more on titanium surface rather than D2 steel work piece. Additionally, damaged layer formed for titanium is thicker than the one produced for D2 steel. High cutting temperature, more energy distributed to the work piece and strong adhesion between the electrode and the titanium lead to poor surface quality in titanium surface. These problems are created due to the low thermal conductivity and high chemical reactivity of titanium alloys.

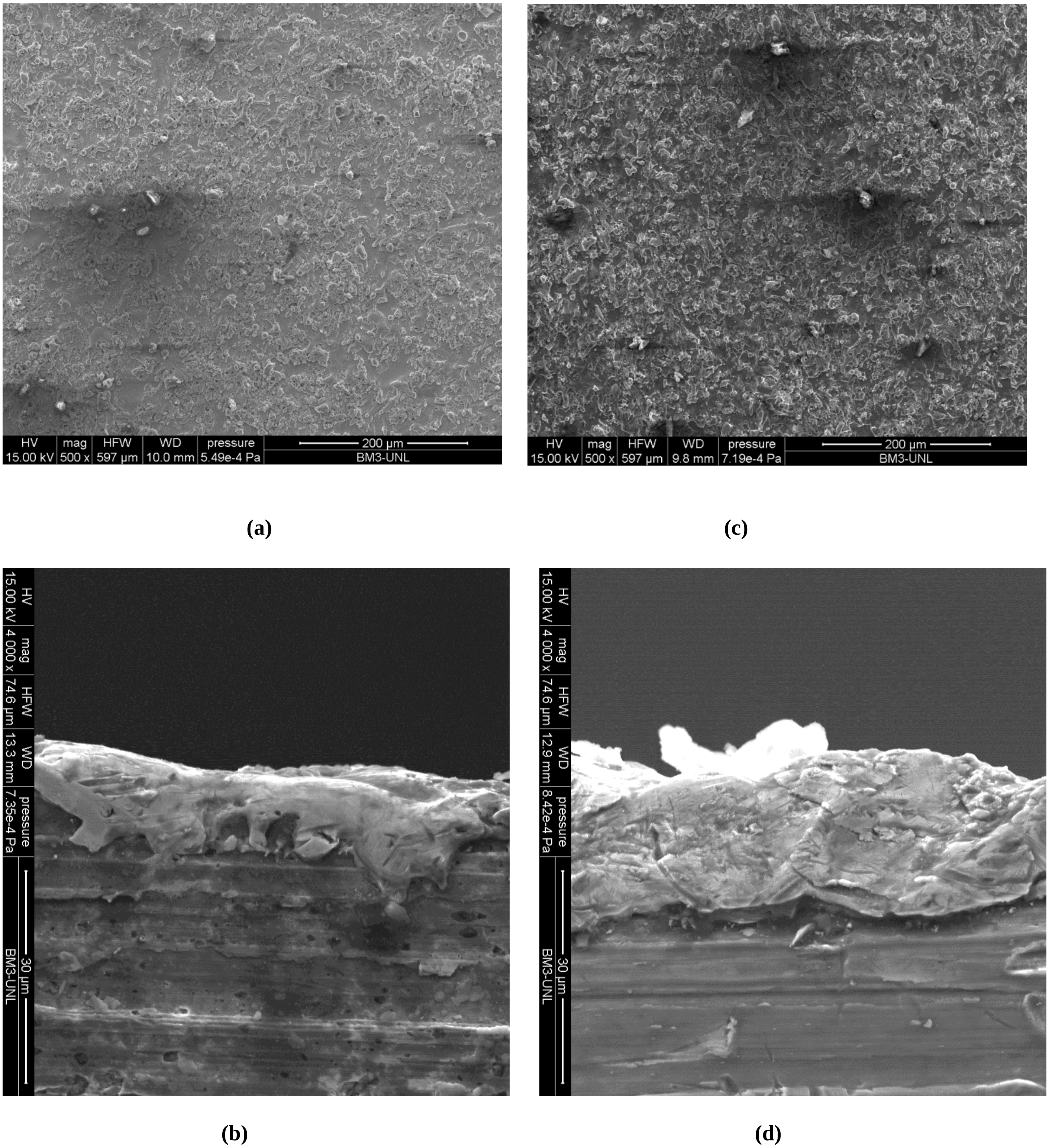


Figure 5.36 SEM Image of D2 Steel Machined with High-Speed Brass Wire and Zinc-Coated Brass Wire

Chapter 6

Wire Properties and Influences on Wire EDM Performance

6.1 Introduction

Wire electrical discharge machining (WEDM) is a non-traditional machining technique that is able to produce complicated and 3-D shapes through difficult to machine metals without using high cost grinding or expensive formed tools [40].

Wire electrical discharge machine should satisfy performance demands such as: high- speed cutting, resistant against wire rupture and accurate machining to improve the productivity and to achieve high quality in machining work pieces [38]. Many factors have effect on the process of WEDM (cutting speed and work piece precision) including electrical parameters and electrode. Higher angles of taper, thicker workpieces, automatic wire threading, and long periods of unattended operation, make choosing the optimum wire a much more critical factor in achieving a successful operation [67].

WEDM system core is wire which is used to receive a stable electrical discharge. So, the wire electrode is one of the important factors contributing the overall WEDM performance [41]. Wire rupture is a serious problem associated to WEDM process and wire electrode. This problem affects surface finish quality and accuracy, limits cutting speed and increases machining time [68].Wire EDM and work pieces requirements vary greatly, which can make selection of the correct wire an acute task. As a result, experimentation with wire types is necessary if optimum results are to be achieved.

In fact, wire breakage poses a constant threat to WEDM productivity, but WEDM operators can avoid wire breakage and keep their operations running smoothly and efficiently with some knowledge about the wire-EDM process, wire rupture causes and the behavior of wire and work pieces materials when they are subject to the process [69].

6.2 Wire Rupture Phenomenon

There are different factors leading to wire breakage such as high wire tension, thermal load, electrical discharge impact and poor flushing. When the developed stresses in wire are more that wire strength, the wire rupture will occur. The developed stresses in wire increase by changing in wire properties and characteristics, cross-section reduction and the increase in wire temperature. High temperature, work piece varying thickness and process parameters influence the wire strength that affects the wire rupture [41,68]. Rjesh Israni provided an experiment to study wire breakages during machining. He figured out the relationship between stresses developed and tensile strength in frequency of wire rupture. He concluded that wire's thermal and mechanical properties have main effect on wire rupture.

The section explains some crucial reasons of wire rupture in details. Also, analysis and experiments are presented to show the effect of machining parametersand thermal load on wire breakage.

Wires rupture probability increases when the work piece thickness changes because the discharge energy changes rapidly. Also, the wire breakage increases when the height of work piece increases. Several research were explored in this subject. They established their own results in machine parameters adjustment and work piece thickness [41]. A multi-input model established to show the stochastic relationship between average gap feedback voltage, discharging frequency and work table feed rate by [70,71].

Some experiments were provided to describe the wire rupture occurs in longer work piece more often due to some factors like wire erosion and flushing condition deterioration. However, these factors do not decrease wire strength and it is more than the stress on wire then the wire breakage happens [68,72].

The excessive thermal load causes wire rupture because of huge heat production on wire electrode and increased wire temperature. The tensile strength of wire decreases when temperature increases. On the other word, the excessive thermal load that consists of internal Joule heat reduces the wire tensile strength during machining. The electrical discharge produces the heat [41,73]. Several researchers studied the thermal energy distribution along the wire electrode and proposed different thermal model with different method.

A thermal model for Wire EDM was developed to describe the temperature distribution along a thin wire in theory. Also, they performed several experiments to establish the effect of thermal load on wire breakage [74]. A mathematical thermal model was proposed in order to examine the relative influence of various process parameters on the thermal load of the wire [34]. Several physical process parameters may increase the probability of wire rupture such as discharge voltage, discharge current, duty factor, coefficient of heat transfer, flushing, wire velocity and the electrical and thermal conductivity of the wire and work piece. If these parameters change, the temperature of wire will increase. Hence, the wire strength is influenced by maximum temperature and wire breakage happens. In fact, the wire rupture can be prevented by controlling above mentioned parameters [73].

A Wire EDM sparking frequency monitoring system was developed to avoid wire rupture based on three features: determination of spark frequency by pulse on-time, frequency, peak current and servo reference voltage, analysis of gap voltage and considering discharge interval

[35]. Rjesh Israni showed the wire rupture decrease when wire velocity increases. The erosion rate and the mechanical stress reduce because the wire has to remain loaded for a shorter time between the current contacts. Also, the wire temperature remains lower and wire strength is higher. Therefore, the wire breakage reduces.

6.3 Influence of Wire Materials on Wire EDM Performance

There are numerous parameters that influence the WEDM performance. New dielectrics, work piece and wire materials are considered as constant factors in order to research the performance of Wire EDM. Among the mentioned factors contribute to improve the WEDM performance, advancement of new materials for wire used in WEDM has a significant impact. In addition, examination and evaluation of the properties of wire materials are very cost effective because the cost of the wire is only about 10% of the WEDM process cost. The high performance of WEDM is measured by low wire breakage, high-speed cutting and high-precision machining [36,75].

The wire used in WEDM should provide some features such as high electrical conductivity, sufficient tensile strength at high temperatures, low melting temperature and high heat conductivity in order to reach to high performance. The high electrical conductivity helps the wire transfers energy to work pieceefficiently and minimize energy loss of sparking during machining. The wire with high tensile strength is a good heat resistance in high temperature and maintains straight under vibration and tension. The low melting temperature of wire improves the spark formation and decrease dielectric ionization time.The higher thermal conductivity of the electrode ensures a better spark discharge energy distribution during the EDM process. This will increase material removal rate [36,38,40,42,67,75].

The performance requirements for a wire electrode are summarized in Figure 6.1. The stable electric discharge leads to high-precision machining and higher cutting speed is achieved by high energy [38].

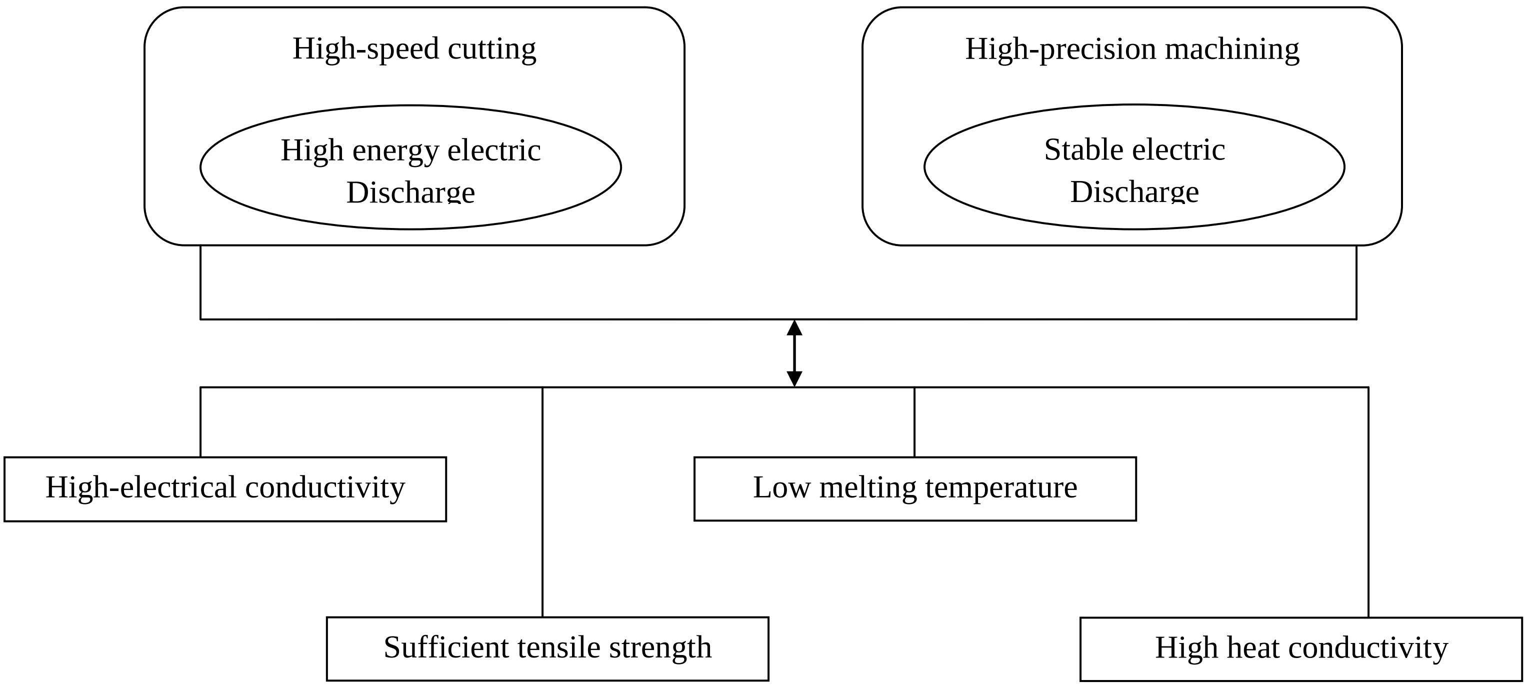


Figure 6.1 Wire Electrode Requirements

A variety of new materials and different types of wire are available to meet the desired characteristics of wire electrode. Recently, many different wire types have been developed with specific properties to give the user a variety of chances.

6.3.1 Plain Wire Electrode

The wire electrodes with a single homogenous component were introduced as plain wire electrodes. These wire types do not consist of coated layer or composite construction.

Copper was the original material first employed as wire electrode in WEDM. Although the excellent electrical conductivity and high elongation of this material satisfies some requirements of wire electrode, its low tensile strength, inability to control vibrationand high melting point lead to slow machining speed, low-precision and tendency wire breakage. Hence, copper application is restricted because of the mentioned problems [38,42,67].

Brass wires were appropriate alternative for copper when WEDM users were looking for a better performance. Brass wires are combination of copper and zinc. They are alloyed in different percentage of 35-37% zinc and 63-65% copper. The tensile strength and vapor pressure rating of brass wire increase because of addition of zinc. Also, the percentage of zinc contain in brass wire reduces its melting point. The cutting performance and speed improve in machining with brass wire due to stable discharge during machining. During the cutting process, the zinc in the brass wire actually boils off, or vaporizes, which helps cool the wire and delivers more usable energy to the work zone. Therefore brass wire has become the commonly applied electrode material since its properties progressed in contrast with copper. However, the brass wire conductivity is significantly decreased. Increasing the zinc content in brass wire can enhance the machining speed (more than 40%) but forming a wire with percentage of zinc that is a brittle phase in the alloy will be difficult. In addition, it was disclosed that the gap conductivity will be further enhanced with more addition of zinc that causes drawing/fabrication problems.

6.3.2 Coated Wire Electrode

The zinc coated wire was produced in order to resolve the previous wire's defectsand to increase substantially the cutting speed and cutting precision. Also, it was mentioned that producing the wire with 40% zinc content is difficult because wire's grain structure changes and it makes brittle.

A conceptual drawing of the structure of the coated wire electrodes is showed in Figure 6.2.

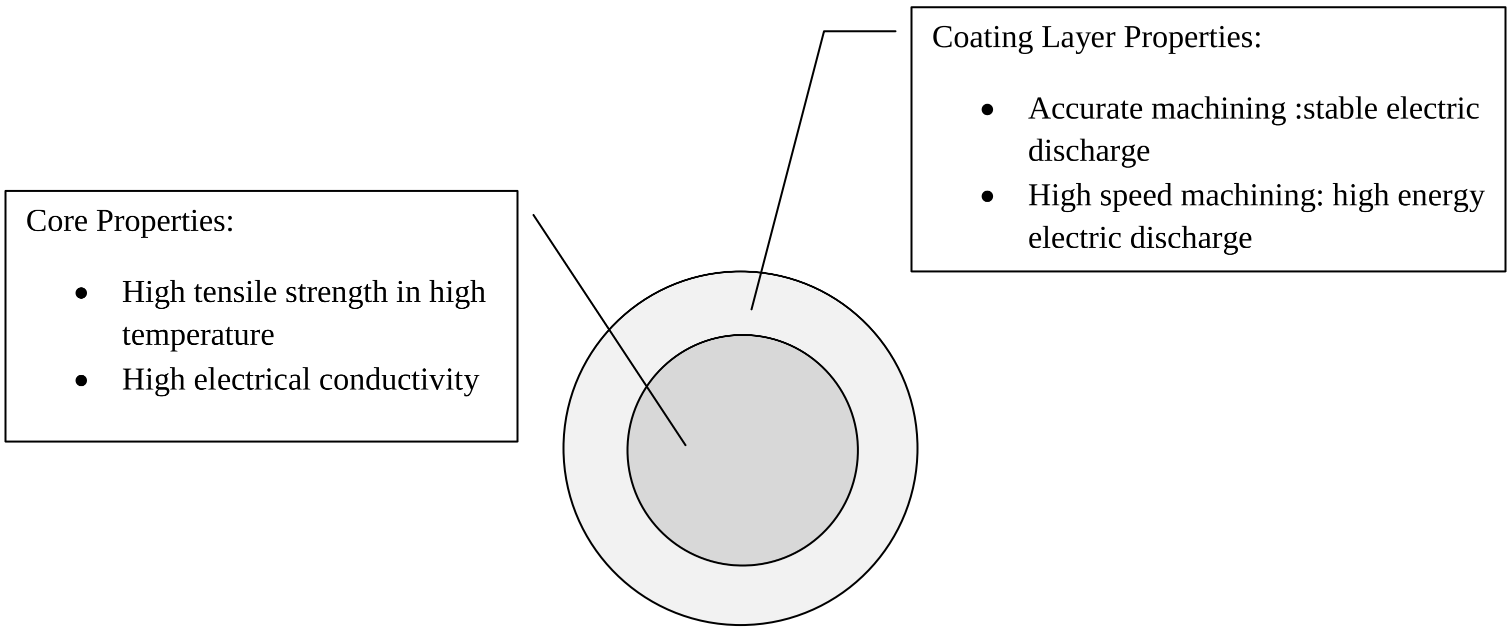


Figure 6.2 Coated Wires Conceptual

There are a restricted number of coating materials available for wires in WEDM. Zinc alloy is the most common material that is applied as the wire coated layer. The zinc alloy was chosen because it has a low vaporization temperature compared with the core material. The wire coating is easily vaporizes when a pulse is applied and core is protected due to cooling effect of coating material.Also, zinc can only be coated on the core of metallic wire because of low melting point. Hence, brass or copper typically are used as core of these type of wires [38,75].

There are several processes of coating such as electroplating, plasma coating, thermal spraying and hot dip galvanizing. However, these methods have many problems such as high cost, uneven concentration of zinc, generation of hazardous gases and change of characteristics of brass wire [38].

An excellent combination of low cost, better flush ability, high mechanical strength and good electrical conductivity are the advantages of zinc coated wires in contrast to brass or copper wires. In addition, the coated layer decreases the risk of rupturing wires because it protects the core of the wire from thermal shock of electrical discharge. All mentioned advantages for zinc coated wires enhance the performance of WEDM, increasing in cutting speed and precision. The thickness of coated wire is typically ~20-30μm [36,40].

6.4 Experimental Procedure

Experiments were done to find the wire characteristics for two wire types, High Speed Brass and Zinc Coated, in association with two work pieces types, Titanium and D2 Steel.The objective was to compare the influence of plain wires and coated wire on WEDM performance. Therefore, the cutting speed, surface roughness and wire rupture are measured for both work piece materials as a scale of comparison. In addition, D2 Steel and Titanium have different specifications that make some differences in Wire EDM efficiency. Titanium alloysare regarded as "difficult-to-machine" materials due to their susceptibility to work hardening during machining and low thermal conductivity and chemical reactivity [14].

The geometry of work pieces and experiment's conditions for both wire materials are same in order to achieve accurate results for comparison.

6.4.1. Wire Rupture

As it mentioned in the previous sections, there are some reasons and phenomena that cause wire rupture during machining. Based on the experiments in this research pulse width (A) and time between two pulses (B) are the most crucial machining parameters that are effective in wire breakage. The wire ruptures probability increases when pulse-width increases and time between two pulses decreases simultaneously. The number of discharges within a given period of time becomes more when time between two pulses (B) is shorter and large pulse duration (A) leads to higher electrical discharging energy which will generate more heat energy. Therefore,due to the excessive thermal load and increased discharge the wire breakage occurs.

On the other hand, wire mechanical tension (Wb) and injection pressure (INJ) are effective parameters in reduction of wire breakage when pulse width and time between two pulses are small and big enough respectively. Wire tension reduction and increase in injection pressure can decrease wire rupture possibility while machining.

Experiments disclosed the frequency of wire rupture in machining of Titanium is more than machining of D2 Steel. Also, wire breakage during Titanium machining is more sensitive to changing of electrical parameters such as time between two pulses, pulse duration, wire tension and injection pressure. The high temperature generated while machining of Titanium due to the low thermal conductivity and high chemical reactivity of titanium alloys results in more wire breakage.

High speed brass wire resistance against wire rupture in tough conditions, high pulse width and low time between two pulses, is much more than zinc coatedwire for both work piece materials. However, coated layer should decrease the risk of rupturing wires because it protects the core of the wire from thermal shock of electrical discharge and increaseswire mechanical tensile strength. In fact, the tensile strength of zinc coated wire is more than normal brass wire but in this case the tensile strength (130,000 PSI) of zinc coated wire is less than the high speed brass wire tensile strength (142,000 + PSI).

6.4.2 Cutting Speed

The range of cutting speed with zinc coated wire is higher than high speed brass wire. The higher cutting speed is more desirable during WEDM machining.

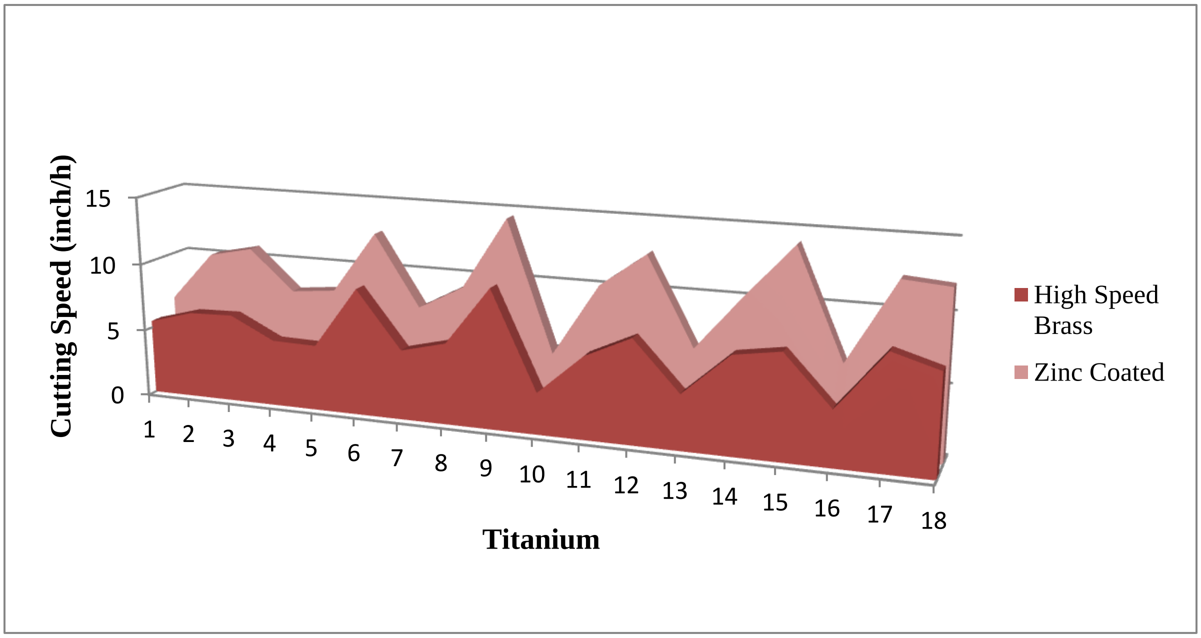


Figure 6.3 Cutting Speed of Titanium for Both Wires

Figure 6.3 shows that the cutting speed of Titanium with high speed brass wire under the same operational parameters is almost one and half times lower than zinc coated. Good sparing properties of zinc layer on brass core result in improving cutting speed. In fact, the addition of zinc to brass wire leads to reduction in the wire melting point. The low melting temperature of wire improves the spark formation and decrease dielectric ionization time. Thus, the cutting rate increases.

6.4.3 Surface Roughness

The surface roughness values for titanium machined with zinc-coated wire brass is less than titanium machined with high speed brass. The small surface roughness is desirable.

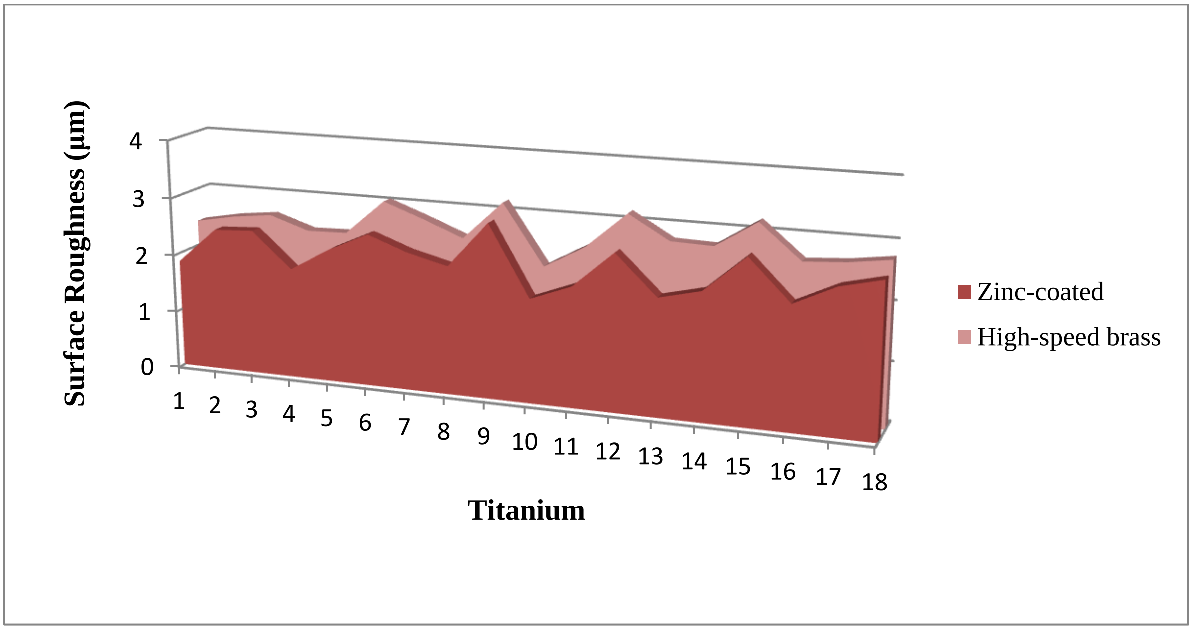


Figure 6.4 Surface Roughness of Titanium for Both Wires

Figure 6.4 proves that zinc-coated brass wire can produce smoother surface in comparison with high speed brass. The existence of zinc in coated brass wire provides higher tensile strength for wire. The wire with high tensile strength is a good heat resistance in high temperature and maintains straight under vibration and tension. Also, the uniform zinc layer on coated wire provides good discharge characteristics. A finer discharge can be created with good discharge characteristics and higher tensile strength. As a result, the quality of work piece surface will improve.

Chapter 7

Data Dependent System (DDS) Analysis

7.1 Introduction

Many attempts have been done to define the random nature of Wire Electrical Discharge Machining (WEDM) process. The objective of these studies was to formulate a quantitative theory for material removal. Unfortunately, these formulations did not clarify the crater geometry and only explained the material removal relation with process parameters [77]. Production of high quality products with Wire EDM is one of the important goals for researchers and industry workers. Therefore, numerous studies have been done about improving and modeling surface roughness. Data-Dependent System (DDS) method was applied to study the random characteristics of surface profiles [78]. An accurate mathematical model can be achieved directly from recorded experimental or observed data by applying DDS methodology without realizing the system [79].

The DDS methodology was used to analyze the stochastic conditions of gap in WEDM by modeling, analyzing and prediction of the process parameters [80]. Also, erosion rate (characteristics crater volume) in WEDM can be predicted in different level of process parameters by applying WEDM surface profiles [81].

In this chapter, the surface roughness profiles of work pieces that are machined by WEDM have been studied by utilizing DDS model. The study provides analysis and modeling of the effect of machining parameters on Wire EDM performance.

7.2 DDS Analysis Approach

A Profilometer was used to measure the surface roughness of the cut samples. The surface profile of each work piece contains heights of 98 points of the surface of the work piece cut. The collected data shows there is a fluctuation on points' heights. So, these data points are appropriate for time series modeling because their trend is not predictable. Time series method can be applied for a natural temporal ordering. This makes time series analysis distinct from other common data analysis problems, in which there is no natural ordering of the observations.

Data Dependent System (DDS) methodology was used to model the data points of the surface. First, data points were loaded as an m-file in MATLAB software. Then, different types of ARMA (n, n-1) were fitted to the data. Various models were tried for each data points to identify the best model. The 95% F-test hypothesis was performed for choosing the best model. The statistically adequate DDS models for the data samples ranged from AR (1) to ARMA (4, 2). A general equation for ARMA (n, m):

$$X_t - \emptyset_1 X_{t-1} - \emptyset_2 X_{t-2} - \emptyset_3 X_{t-3} - \ldots - \emptyset_n X_{t-n} = a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} - \ldots - \theta_m a_{t-m} \quad [7.1]$$

$E(a_t) = 0$ and $E(a_t a_{t-1}) = \delta_k \sigma_a^2$.

Where E = expected value and

δ_k = the Kronecker delta (where δ_k = 0 for all values of k, except δ_k = 1 for $k = 0$).

a_t = White noise term

$\emptyset_i$ = Autoregressive Coefficient

θ_j = Moving Average Coefficient

The concept of Green's Function and Spring-mass-dashpot System are explained by using a second order model since it was the most proper time series model for most of the surface profiles.

7.2.1 Green's Function

Green's function is an equation that describes the behavior of the model to small differences of something or some quantity such as time or space. Also, a Green's function represents the "response" of a system to a special type of input.

The explicit expression for Green's function of second order model is: $G_j = g_1\lambda_1^j + g_2\lambda_2^j$

$G_0 = 1$ all the time.

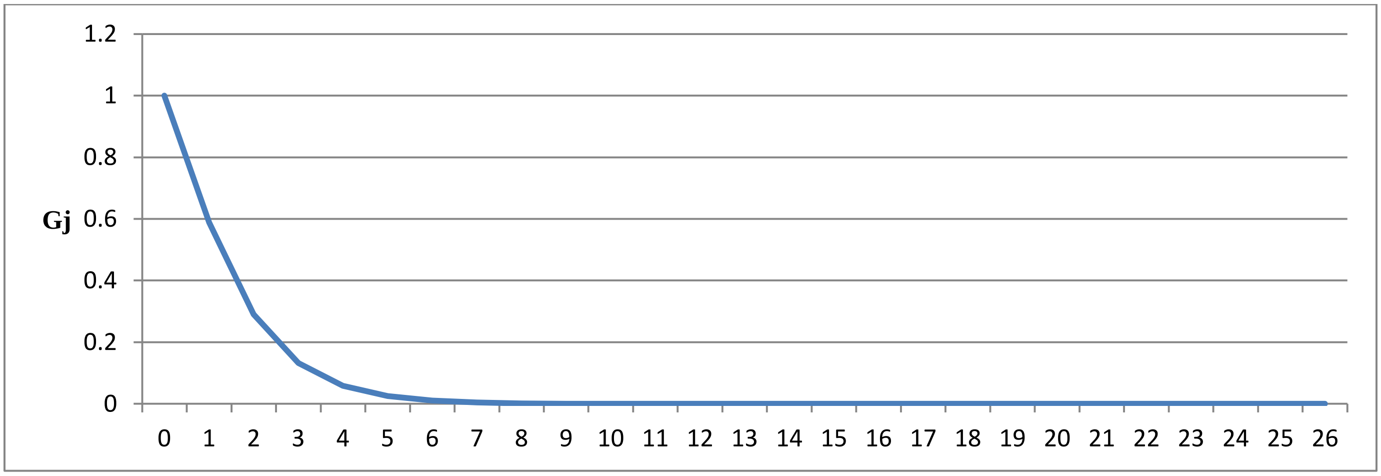


Figure 7.1 Green's Function Diagram

The Green's Function converges to zero. So, the system is asymptotically stable. Also, Figure 5 shows the Green's Function after around point 12 converges to zero. In fact, this graph indicates that system will forget noises and return to balance position after 12 points.

7.2.2 Spring-mass-dashpot System

Based on the nature of the mathematical model used, the system may be called a discrete system or a continuous (or distributed) system. In the discrete model, the physical system is assumed to consist of several rigid bodies (usually considered as point masses) connected by springs and dampers. The springs denote restoring forces that tend to return the masses to their respective undisturbed states. The dampers provide resistance to velocity and dissipate the energy of the system.

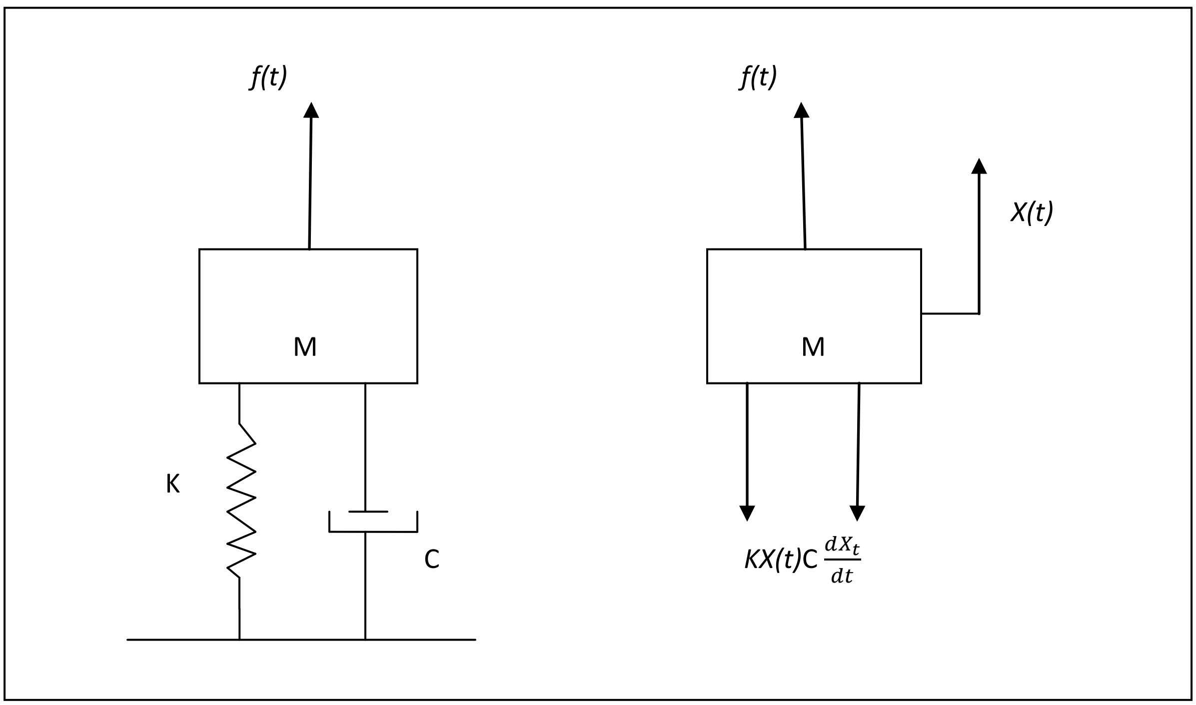


Figure 7.2 Spring-Mass-Dashpot System

$\mu_1 = -\zeta\omega_n + \omega_n\sqrt{\zeta^2 - 1}$ $\mu_2 = -\zeta\omega_n - \omega_n\sqrt{\zeta^2 - 1}$

$\mu_1 \times \mu_2 = \omega_n^2 \mu_1 + \mu_2 = -2\zeta\omega_n$

If $\zeta>1$ we can classify this system in over-damped group so, the system slowly return to equilibrium.

Spring Mass Dashpot System Parameters	**Corresponding Factors**
Mass (M)	Work piece Surface
Dashpot Constant (C)	De-ionized Water
Spring Constant (K)	Wire vibration

Table 7.1 Modeled System Parameters

The system that is modeled by time series can be defined based on the spring-mass dashpot system parameters (M, C and K). In this system, cutting a work piece with wire EDM, mass represent work piece surface that is affected by sparks generated (here it is force). Then, spring constant in this system is wire vibration. There is some research that attempted to study the dynamic in-process mechanical behavior of the wire because the wire-tool vibration during machining has a great effect on the machining performance. As a result, the density of spark discharges would also be changed depending on the shape of the mode of vibration. This will have an impact on the precision and accuracy of the work piece [82]. Also, the de-ionized water can be referred as the spring constant that reduces (or removes) force impact and returns system to equilibrium state.

7.3 Characteristic Crater Based on the First Order Model

There are various investigations that have utilized first order model in order to predict the crater behavior. The surface profiles of work pieces generated under multiple discharge condition have been used to measure the volume of a crater in terms of DDS parameters. They used first order stochastic differential equation to model Electro-Discharge machined surface profiles [77, 79, 81].

The objective in this part is comparing the crater size at different machining parameters. Thus, a same methodology has been applied to satisfy the objective. The first order model was not statistically adequate for all of them. Therefore, other models were forced to be AR (1) model in order to analyze crater characteristics. The following equations represent the first order model form:

$$\frac{dx(t)}{dt} + \alpha_0 x(t) = z(t) \quad [7.2]$$

$$E[z(t)z(t-u)] = \sigma_z^2 \delta_{(u)} \quad [7.3]$$

Where $x(t)$ is the measured height of the surface

α_0 is the autoregressive parameter.

The parameters of first autoregressive model (AR (1) model), $\emptyset_1$ and σ_a^2 are obtained from MATLAB program. Other parameters such as α_0 and σ_z^2 can be calculated by the following formulas:

$$\alpha_0 = -\frac{\log \emptyset_1}{\Delta} \quad [7.4]$$

Where Δ is the sampling interval.

$$\sigma_z^2 = \frac{2\alpha_0 \sigma_a^2}{(1-\emptyset_1^2)} \quad [7.5]$$

Based on the first autoregressive model parameters the volume of crater can be calculated. In two dimensional spaces, the Green's Function shape can represent a half section of crater. The parameters σ_z^2 and $\frac{9}{\alpha_0}$ can be considered as depth and diameter of crater representatively in order to render a physically meaningful concept of characteristic crater. The volume of characteristic crater of any depth is given by the following equation [77].

$$V_e = (0.512)(\sigma_z^2)^3 (\frac{9}{\alpha_0})^2 \quad [7.6]$$

The characteristics crater volume of machined work pieces by both type of wire electrodes in different level of machining parameters are given in Table 7.2. Other parameters such as V and IAL were fixed during the experiments in -80 and 6A respectively.

Zinc-Coated Brass Wire Electrode						
A	B	Aj	INJ	Wb	$\sigma_z^2\ \mu m$	Ve $10^6\ \mu m^3$
0.3	14	30	5	0.7	108.469	1.33
0.5	18	40	7	0.9	141.257	1.63
0.7	20	50	9	1.1	188.627	1.87
High-Speed Brass Wire Electrode						
A	B	Aj	INJ	Wb	$\sigma_z^2\ \mu m$	Ve $10^6\ \mu m^3$
0.3	14	30	5	0.7	207.027	2.63
0.5	18	40	7	0.9	354.494	3.04
0.7	20	50	9	1.1	433.256	3.29

Table 7.2 Characteristics Crater Volume

Figure 7.3 shows the volume of characteristic crater for each wire electrode. It can be seen that the volume of characteristic crater (V_e) increases with increasing machining parameters such as pulse width, time between two pulses, servo reference voltage, and injection pressure and wire tension.

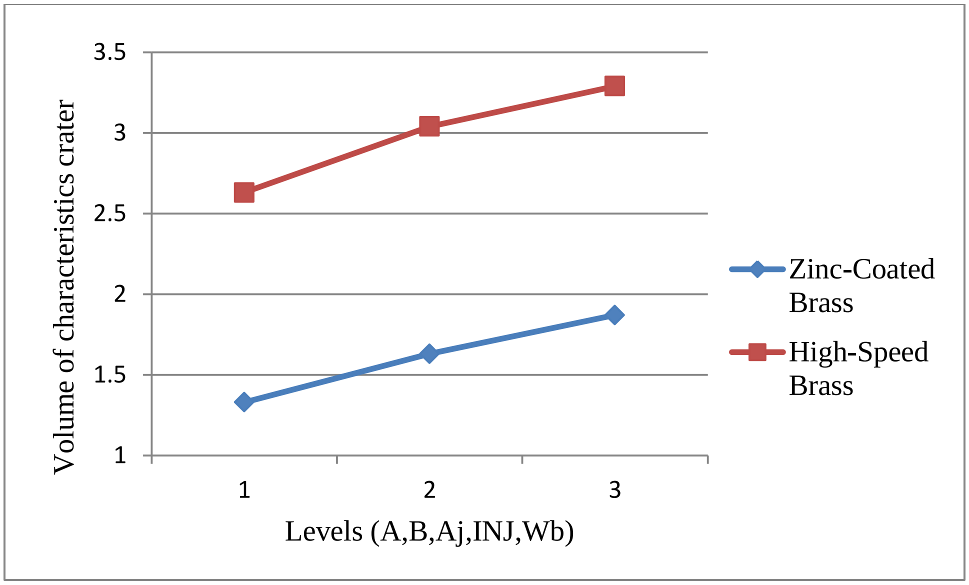


Figure 7.3 Volume of Characteristic Crater

Table 7.3 shows the volume of characteristic crater that were calculated in different levels of pulse width and pulse current for both wire types.

Zinc-Coated Brass Wire Electrode			
A	IAL	$\sigma_z^2\ \mu m$	Ve $10^6\ \mu m^3$
0.3	6	108.469	1.33
0.5	9	137.329	2.02
0.7	12	153.372	2.68
High-Speed Brass Wire Electrode			
A	IAL	$\sigma_z^2\ \mu m$	Ve $10^6\ \mu m^3$
0.3	6	207.027	2.63
0.5	9	579.251	3.36
0.7	12	795.509	3.7

Table 7.3 Volume of Characteristic Crater

Figure 7.4 shows that increasing the pulse width and pulse current improve the material removal rate in machining of titanium with both wire types. In the other word, the discharge energy enhances when pulse width and pulse current increases thus generating a larger crater or higher material removal rate.

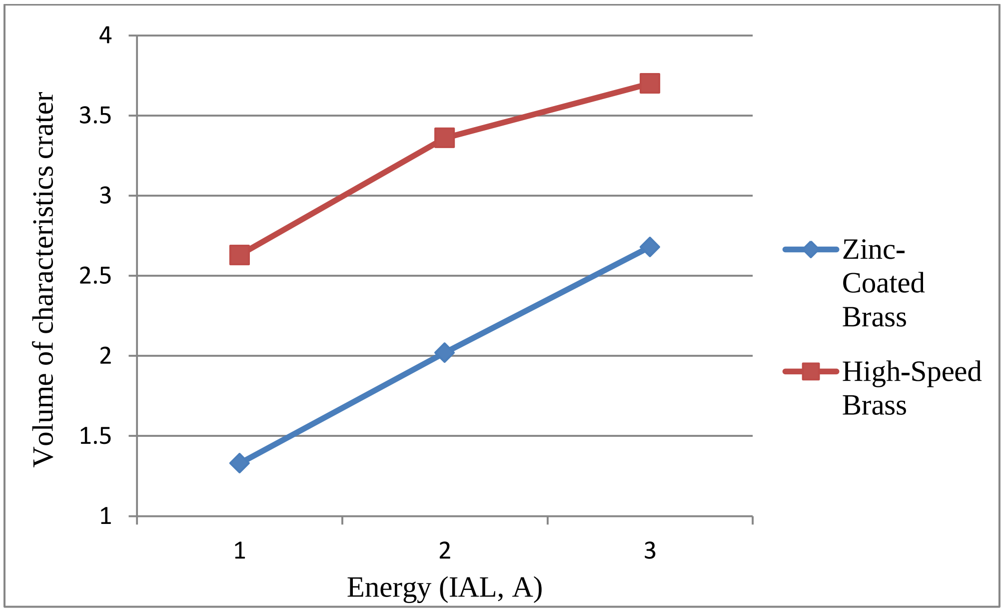


Figure 7.4 Volume of Characteristic Crater

In addition, it can be seen that the characteristic crater value of high-speed brass wire is more than zinc-coated wire in each level of parameters because the high-speed wire data points' variance is greater than the other wire's data point's variance. It means data points (results) deviate from the mean value more often. This is reasonable since it was mentioned before that the surface roughness obtained with zinc-coated wire is smoother. As a result, σ_z^2 and volume of characteristic crater increase more.

Chapter 8

Conclusion and Recommendations

8.1 Conclusion

In this study, the influence of zinc-coated brass wire on the performance of WEDM (wire breakage, cutting speed and surface roughness) was compared with high-speed brass in order to develop an approach to perform a high performance and cost efficient WEDM of Ti6Al4V. Also, various machining conditions were investigated to determine the effect of process parameters on the process responses (wire breakage, cutting speed and surface roughness). Data Dependent System (DDS) was applied to model the Wire Electrical Discharge Machined surface profiles. Based on the experiments and analysis, the following conclusions can be drawn:

- The time between two pulses and pulse width have significant effect on cutting speed in machining of titanium with both wire types.
- Peak current, time between two pulses and servo reference voltage mean are effective parameters in machining of D2 Steel with both wire types.
- As pulse width and peak current increase, the cutting speed increases. This is due to the increase in discharge energy and enhancement in pulse width and peak current that lead to a faster cutting rate. However, the increase in time between two pulses and servo reference voltage results in decreased cutting speed. The increase in servo reference mean voltage results in widened average discharge gap thus leading to a lower cutting rate.

Also, the number of discharges within a given period decreases due to the increase in the time between two pulses which results in lower cutting rates.

- In machining of D2 steel with both wire types, pulse width and time between two pulses have significant effects on surface roughness.

- Peak current, pulse width and wire tension are significant factors in machining of titanium with zinc-coated wire and high-speed brass wire.

- As the pulse width and peak current increase, surface roughness increases due to increase in the discharge energy. The larger discharge energy produces a larger crater, causing a larger surface roughness value on the work piece. Also, increase in wire tension and time between two pulses causes reduction in surface roughness. When time between two pulses decreases, the number of discharges increases which leads to higher surface roughness accuracy. Also, increase in wire tension results in reduced vibration which enhances surface roughness accuracy.

- The wire ruptures probability increases when pulse-width increases and time between two pulses decreases simultaneously. Also, Wire tension reduction and increase in injection pressure can decrease wire rupture possibility.

- Zinc-coated brass wire results in higher cutting speed and smoother surface finish compared with high-speed brass wire,. Also, SEM photographs prove that uncoated wire produces a surface finish with more cracks, craters and melted drops. In addition, the thickness of damaged layer of machined parts with zinc-coated wire is lower than the parts machined by high-speed brass wire. Zinc-coated wire has good electrical conductivity that helps the wire transfer energy to work piece efficiently. Thus, it leads to low heat energy in the part's surface and decreases the size of damaged layer.

- High speed brass wire resistance against wire rupture in tough conditions, high pulse width and low time between two pulses is much more than zinc coated wire. This is due to smaller tensile strength (130,000 PSI) of zinc coated wire compared with the high speed brass wire tensile strength (142,000 + PSI).

- Various statistical models were tried for each data points to identify the best model. The 95% F-test hypothesis was performed for choosing the best model. The statistically adequate DDS models for the data samples ranged from AR (1) to ARMA (4, 2). Also, Green's Function and spring-mass-dashpot system were presented for model ARMA (2,1).

- In order to analyze crater characteristics, all models were fixed to be AR (1) model, resulting in loss of information. The results indicate that increase in some machining parameters such as pulse width, time between two pulses, servo reference voltage, and injection pressure and wire tension could increase the volume of characteristic crater (V_e).

- The characteristic crater value of high-speed brass wire is more than zinc-coated wire in each level of parameters. The reason is that the high-speed wire data points' variance is greater than the other wire's data point's variance.

8.2 Recommendations

- In this study, the effect of some machining parameters was investigated on wire rupture, cutting speed and surface roughness. One extension of this study can be analysis of the influence of other machining parameters, machining conditions and components on Wire EDM performance.

- This study showed zinc-coated brass wire results in higher cutting speed and smoother surface finish in comparison with high-speed brass. It may be more practical to investigate the performance of other wire types such as composite wires, wires with other coated layer types or different core materials.

- Two different wire types were used to study their effects on surface roughness, cutting rate and wire breakage. The effect of other wire's properties such as shape and size can be analyzed in a separate study.

- The experimental results showed that the wire breakage in machining of titanium is sensitive to electrical process parameters such as time between two pulses, pulse width, wire tension and injection pressure. Investigation should be extended to include other factors in the study.