EXPERIMENTAL INVESTIGATION OF FERROUS ALLOY USING WIRE-CUT EDM PROCESS

A Dissertation submitted in partial fulfillment of the award of Degree of

MASTER OF TECHNOLOGY
IN
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Submitted by:

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Under the guidance of:

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CERTIFICATE

This is to certify that thesis entitled, "**Experimental investigations of ferrous alloy using Wire-cut EDM**" submitted by Mr. Ujjwal in partial fulfillment of the requirements for the award of Master Of Technology in Mechanical Engineering with "Production Engineering" Specialization during session 2012-2014 in the Department of Mechanical engineering, Delhi Technological University, Delhi.

This work is carried out by him under my supervision and guidance. To the best of my knowledge, the matter embodied in this thesis has not been submitted to any other University/Institute for award of any Degree or Diploma.

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STUDENT DECLARATION

This is to certify that thesis entitled, “***Experimental Investigations of Ferrous Alloy Using Wire-Cut EDM”*** submitted by **Mr. Ujjwal** (Roll No.: **2K12/PRD/25**) is an authentic record of own work carried out by me.

I also certify that there is no plagiarism material in this report and has not been submitted to any other Institute/University for the award of any degree or diploma.

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ABSTRACT

Wire-Cut Electrical Discharge Machining (WEDM) is more appropriate techniques for machining difficult–to-machine materials. Electrically conductive materials are cut by Wire-cut 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 Wire-cut EDM methodology, the mechanical stress and vibration problems in machining are eliminated.

The focus of this investigation is on machining of AISI H-13 Die steel material with Wire-cut EDM and to study the effect of coated and uncoated wires electrodes on machining performance and wire breakage phenomenon. In this investigation, study of effect of process parameters including Pulse-on Time, Pulse-off Time, Wire Feed-rate and Wire Tension on process performance parameters such as cutting Speed, metal removal rate and surface integrity are investigated. All experiments were conducted using FANUC ROBOCUT Alpha 1-iE CNC Wire-Cut EDM. A Taguchi L9 Design of Experiment (DOE) is applied to determine the effect of significant parameters on Wire-cut EDM performance. To analyze the date, analysis of variance (ANOVA) has been use to find the optimal levels for each process parameter. Several experiments are done in order to find the effect of machining parameters and their setting on wire breakage.

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CHAPTER 1

Introduction

The history of Electrical Discharge Machining (EDM) Machining Techniques goes as far back as the 1770s when the effect of the 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].

When it was originally observed by Joseph Priestly in 1770, his EDM Machining was very imprecise and riddled with failures. It was commercially developed in the mid 1970s. **Wire-Cut Electrical Discharge Machining (EDM)** began to be a reliable technique that helped shape the metal working industry as we see today. In the mid 1980s, their EDM techniques were transferred to a machine tool system. This migration was made EDM more widely available and appealing over traditional machining processes.

The new concept of machining uses non-conventional energy sources like the sound, light, mechanical, chemical, electrical, electrons and ions. With the new industrial and technological growth, the development of harder and difficult to machine materials, which find wide application in various field like aerospace, nuclear engineering and other industries owing to their sufficient high strength to weight ratio, hardness and the heat resistance qualities has been witnessed. New developments in the various field of material science has led to new engineering metallic materials, new composite materials and new range of high tech ceramics having good mechanical properties and thermal characteristics as well as having sufficient electrical conductivity so that they can readily be machined by Wire-cut EDM [2].

1.1 Electric Discharge Machining (EDM)

Electric Discharge Machining (EDM) is an electro-thermal non-traditional machining process in which electrical energy is used to generate electrical spark between electrode and workpiece and material gets removed mainly due to thermal energy of the spark. EDM process is mainly used to machine difficult-to-machine materials and high strength temperature resistant alloys. EDM machining even used to machine difficult geometries in small batches or even on job-shop basis. Work-piece material to be machined by EDM has to be electrically conductive.

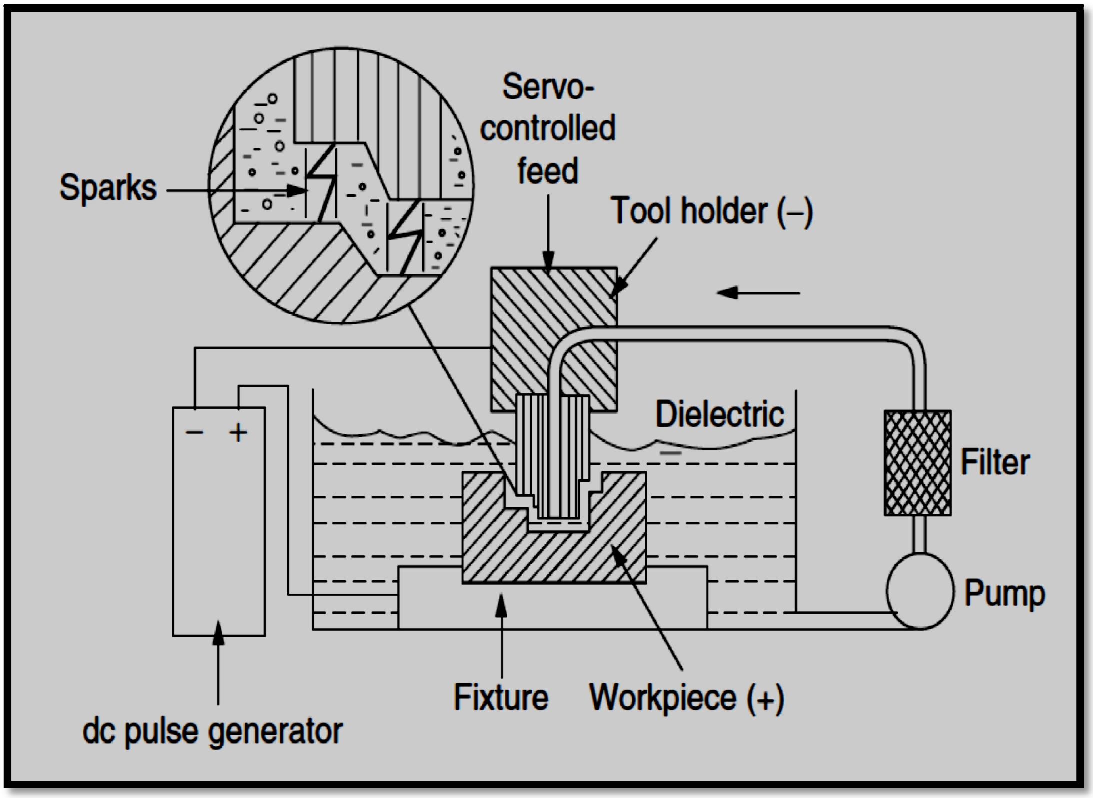


Figure 1.1: Set up of Electric Discharge Machining [3].

In this machining process, the metal is removing from the work-piece material due to erosion case by rapidly reoccurring spark discharge taking place between the tool (electrode) and work piece material. A thin gap about 0.025mm is maintained between the tool and work piece material by a servo system as shown in Figure (1.1). Both tool (electrode) and work piece material are submerged in a dielectric fluid .Kerosene oil/EDM oil/deionized water are very common type of dielectric fluids used in EDM machining although gaseous dielectrics are also used in certain cases of machining.

This Figure (1.1) is shown the electrical setup of the Electric discharge machining. The tool (electrode) is made cathode and work piece material anode. When the voltage across the gap becomes sufficiently high it starts discharging through the gap in the form of the spark in the interval of 10 micro seconds. And the positive ions and electrons are accelerated, producing a discharge channel of ions that becomes conductive to flow energy. It is just at a point in time when the spark jumps causing collisions between ions and electrons and creating a channel of plasma [4]. The sudden drop in the electric resistance of the previous channel allows that current density reaches very high values producing an increase of ionization and the creation of a powerful magnetic field. The moment spark occurs sufficiently, the pressure developed between work and tool as a result of which a very high temperature is reached and at such high pressure and temperature (8000°C-12000° C) that some metal is melted and evaporated at the same time.

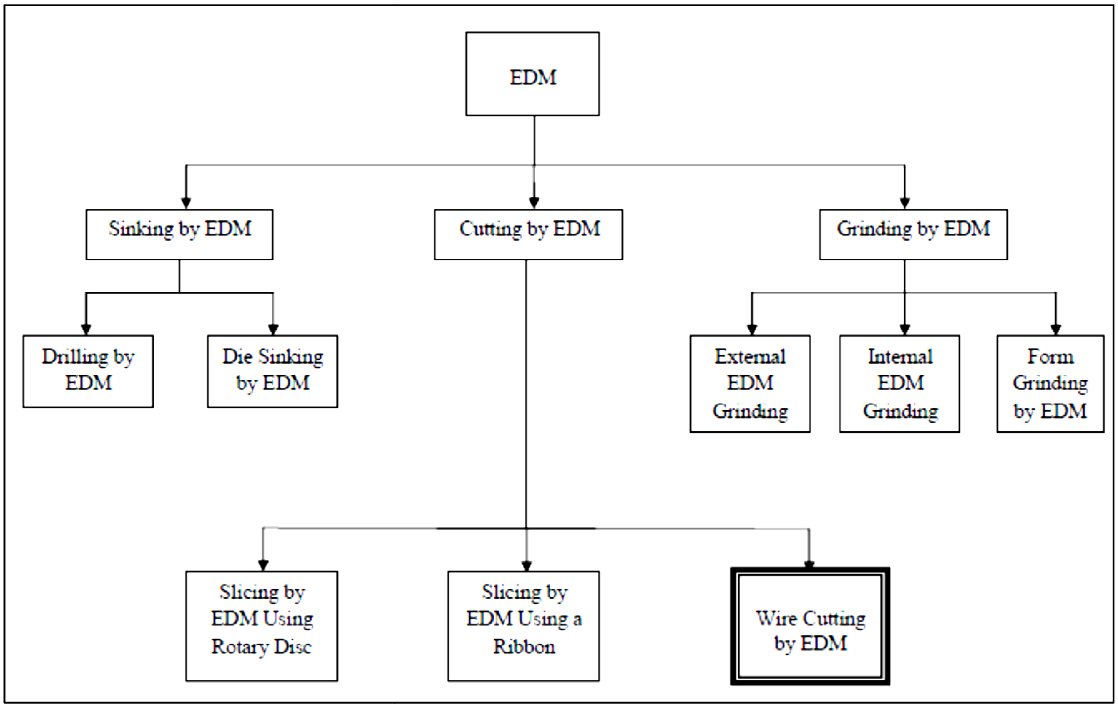


Figure 1.2 : Classification of EDM [5].

Such localized extreme rise in the temperature leads to material removal in workpiece material. Material removal occurs due to instant vaporization of the workpiece material as well as due to melting. The molten metal is not completely removed, but only a part of it.

There are several different EDM processes as shown in the Figure (1.2) [5].

1.2 Wire-Cut Electric Discharge Machining

Wire-Cut EDM Machining process is an electro-thermal production process in which a thin single-strand metal wire (usually brass) in conjunction with dielectric fluid (used to conduct electricity) allows the wire to cut through the metal by the use of heat generated from electrical sparks. A thin single-strand metal wire used as electrode, usually brass, is fed through the workpiece material, submerged in a tank of dielectric fluid; typically fluid is deionized water as shown in Figure (1.3). Wire-cut EDM is widely used to cut plates as thick as 300mm and to make punches, tools and dies from hard metals that are difficult to machine with other methods [6].

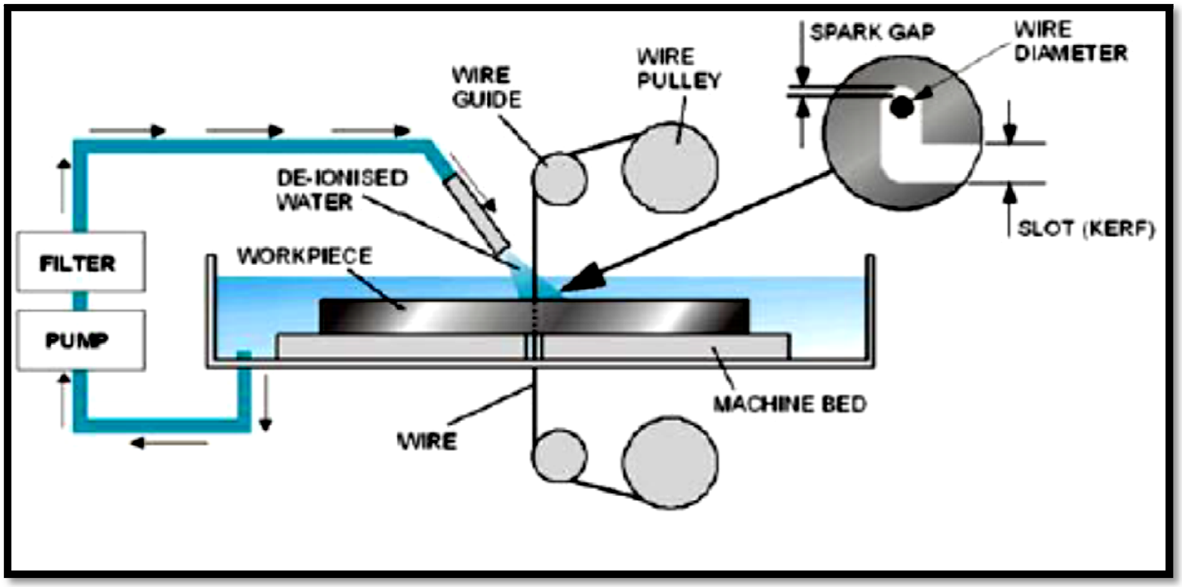


Figure 1.3: Schematic Diagram of Wire-Cut EDM System [7].

In this, mechanism of metal removal mainly involves the removal of material due to melting and instant vaporization caused by the electric spark discharge generated by a pulsating direct current power supply between the wire (electrode) and workpiece material. In this process, a continuously moving wire is negative electrode and the positive electrode is the work piece material. The applied voltage across electrodes creates a channel of plasma in the working gap which is immersed in de-ionized water.

A pulsating discharge spark takes place with heavy flow of current and the resistance of the ionized channel gradually decreases. A high intensity of current value continues to further ionize the channel and a powerful magnetic field is being established. This magnetic field compresses the ionized channel and results in high localized heating. Even with the sparks of very short duration, the electrodes temperature can locally rise to very high value which is more than the melting point of the workpiece material due to transformation of the kinetic energy of electrons into heat energy.

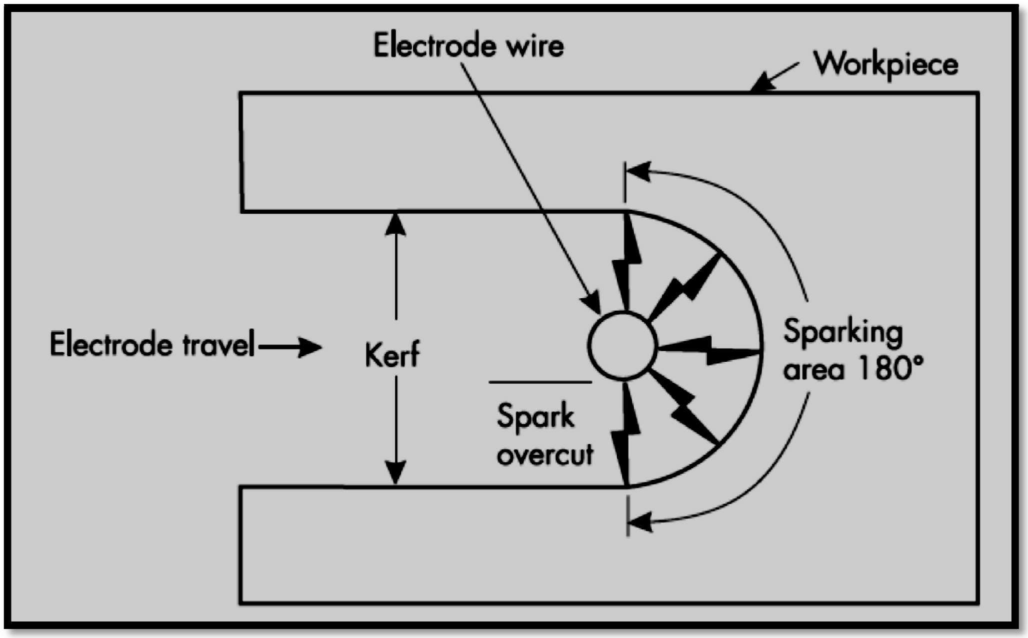


Figure 1.4: Wire-cut EDM sparking area [8].

The high energy density erodes a part of material from both the wire as well as workpiece material by locally melting and vaporizing and thus it is the dominant thermal erosion process. Wire-cut sparking occurs between the side and machined surfaces of the workpiece. Spark length is set by the machine controls. The sparking area consists of only the front 180° of the wire electrode diameter as it progresses into the cutting as shown in Figure (1.4).

A clearance equal to the spark length is machined on each side of the wire electrode. This side clearance is the spark overcut. The total width of the machined opening consists of the electrode diameter, plus two times the spark length. The total width of the machined opening is the kerf width as shown in Figure (1.5).

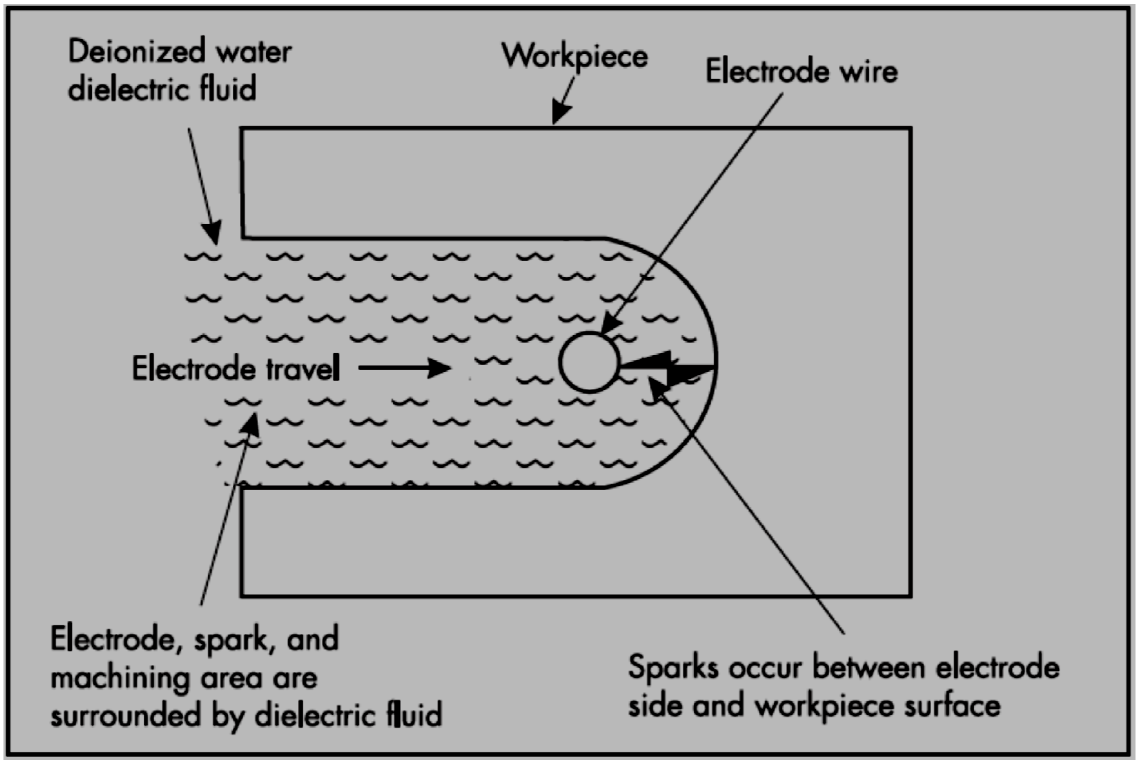


Figure 1.5: Wire-cut EDM sparking from electrode side [8].

Wire-cut EDM machining is commonly used when low residual stresses are desired, because it does not require a high cutting force for removal of material. If the energy per pulse is relatively low (as in most finishing operations), a very little change in mechanical properties of a workpiece material occurs because of low residual stresses, although the material that hasn't been stress-relieved can distort in the machining process.

Good inherent properties of the process makes the wire-cut EDM machining capable of to make easily machine complex parts and precision components out of hard conductive materials in industry.

1.2.1 Advantages OF Wire-Cut EDM

- Mechanical stress is completely eliminated during machining since there is not any contact between wire electrode and work piece.

- This process is able to produce more complicated workpiece in different shapes and size.
- Wire-cut EDM process can also be applied for repairing damaged parts.
- Any material which is electrical conductive can be machined by Wire-cut EDM process apart from its properties like hardness, toughness and brittleness.

1.2.2 Disadvantages OF Wire-Cut EDM

- A high investment is required for Wire-cut EDM electrode and machine tool.
- This process has a problem regarding the formation of recast layer on the machined part surface.
- Wire-Cut EDM process shows very slow cutting rate.
- Wire-Cut EDM process is not applicable for machining very large work piece.

1.2.3 Applications of Wire-Cut EDM

The present applications of Wire-cut EDM process in various fields like automotive, aerospace, mould tool and die making industries. Wire-cut EDM applications can also be found in other fields like medical, optical, dental, jewellery industries, and in automotive and aerospace R & D department areas .The machine's ability to operate unattended for hours or even days further increases the attractiveness of the process. Most Machining thick sections of material, as thick as 200 mm, in addition to using computer to accurately scale the size of the part, make this process especially valuable for the fabrication of dies of various types. The machining of press stamping dies is simplified because the products like punch, die, punch plates and stripper, all can be machined from a common CNC program.

Without Wire-cut EDM, the fabrication process requires many hours of electrodes fabrication for the conventional EDM technique, as well as many hours of manual grinding and polishing. With Wire-cut EDM, the overall fabrication time is reduced by 37%, however, the processing time is reduced by 66%. Another popular application for Wire-cut EDM is the machining of extrusion dies and dies for powder metal (PM) compaction.

CHAPTER 2

LITERATURE REVIEW

In this session literature survey carried out is reported. Brief summary of the main papers is described below:

R.E. Williams, K.P. Rajurkar [9] studied the complex and random nature of the erosion process in Wire-cut EDM process. They present the results of investigations into the characteristics of Wire-cut EDM generated surfaces. The surface roughness profiles were studied with a stochastic modeling and analysis tool methodology to have a better understanding of process mechanism. A Scanning electron microscopic (SEM) examination is being done to highlight the important features of Wire-cut EDMed surfaces.

T. Matsuo, E. Oshima [10] investigated performance of Conductive zirconias containing 23 to 45 vol% NbC or Tic through wire-cut edm machining. They were evaluating machining rate and surface roughness for various pulse duration and duty factors and discuss the optimum machining conditions for the wire-cut EDM process. They also investigate the effect of second cut on the machining rate and surface roughness response parameters under set of conditions of machining.

M. Kunieda, H. Nakano, W. Kadowaki [11] describes the evaluation of the temperature of wire electrode in the wire-cut electrical discharge machining (Wire-cut EDM). They have a principle of measuring temperature which is based on the fact that the sensitivity of the method of measuring spark discharge locations in the Wire-cut EDM processes is affected by temperature of the wire electrode.

N. Mohri, H. Yamada, K. Furutani, T. Narikiyo, T. Magara [12] studied that it is very important to restrain the vibration of the tool wire electrode for the improvement of machining accuracy in wire-cut EDM process. They carried out their investigation towards the dynamic wire vibration mechanism and for that they proposed a mathematical model. The resulted displacement of a wire electrode in machining a thin plate is analyzed with a impulsive force measured through impulse response by a single spark discharge. The force acting on the wire electrode depends on the direction of the wire movement in vibration. A 3^{rd} order system equation for the wire-cut EDM system is established considering machining removal and vibrational features of the system are discussed with the equation.

W.J. Hsue, Y.S. Liao, S.S. Lu [13] studied the phenomenon of corner cutting in wire-electrical discharge machining. They predict that the sudden increase of gap-voltage resulted as abrupt MRR drop and amount of the drop at the corner apex is dependent on the angle of the turning corner. They take the wire federate, wire tension flushing rate in both upper and lower guide as process parameters and their response on MRR as well as discharge rate at corner cutting. The observed phenomenon of increased gap-voltage and decreased sparking frequency in corner cutting can be physically interpreted. In addition, the variation of the machining load caused by the change of MRR, which was taken as unknown disturbance in the past, can be predicted and used for control purpose.

Kevin D. Murphy, Zhengmao Lin [14] investigate the effect of spatially non-uniform temperature “fields” on the free vibration and stability characteristics of the wire electrode in the wire electro-discharge machining (EDM) process. They studied the wire temperature field along it. In particular, a non-linear multi-mode structural model is developed for the translating wire along with a thermal model which accounts for heat input (from sparking), axial conduction, radial convection, and energy storage. They used two mathematical models, equilibrium and eigenvalue analyses show that the transport speed has a profound influence on the stability of the straight equilibrium configuration. Specially, at more high speeds, the straight configuration is rendered unstable by a series of pitchfork bifurcations. The temperature field also has a significant influence on the straight wire configuration but at low speeds. Here, the wire has an extended residency time in the response kerf width and the wire thermally buckles.

Nihat Tosun [15] studied the various process parameters pulse time, open circuit voltage, wire speed and dielectric fluid pressure experimentally on wire-cut edm process on AISI 4140 steel having 10mm thickness with 0.25 brass wire electrode to see the effect on response parameters which are surface roughness and cutting speed. He found that increasing pulse time, open circuit voltage, wire speed and dielectric fluid pressure increases the surface roughness and cutting rate. He uses a regression analysis method to perform modeling for cutting speed and surface roughness.

A.B. Puri, B. Bhattacharyya [16] studied the wire lag phenomenon in Wire-cut Electrical Discharge Machining (Wire-cut EDM) and the trend of variation of the geometrical inaccuracy as shown in Figure (2.1) caused due to wire lag with various machine control parameters has been established in paper.

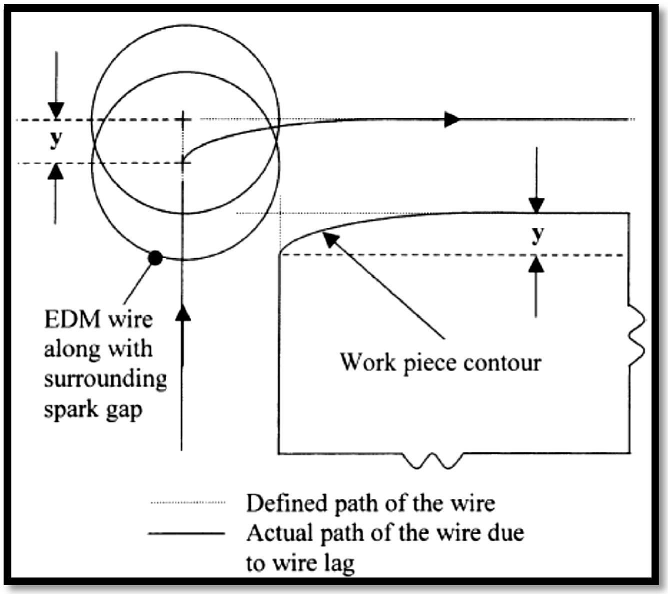


Figure 2.1: Illustration of the effect of wire lag on the workpiece contour [45]

They uses taguchi’s orthogonal array L_{27} to conduct the experiments with three levels of each thirteen control factors which are as Pulse Peak voltage, Water pressure, Wire feed rate, Wire tension, Servo Set Voltage, Flow rate, Offset of Wire, Cutting speed etc. A wire-cut EDM machine, supercut-734, was used for conducting the L_{27} experiments with a typical die steel (M2-hardened and annealed) with 0.25mm brass wire. Cutting speed (V_c), Surface roughness (Ra) and geometrical inaccuracies (*g*) is being analysed in this study. Signal to noise ratio and ANOVA (analysis of variance) are used as tools to analysis the responses. They seen that high tension is better to reduce the amplitude of wire-tool vibration and higher the thickness of the workpiece result into the larger will be the maximum amplitude of vibration for a given span of the wire between the guides.

A.B. Puri, B. Bhattacharyya [17] also studied the vibration behaviour of the wire and presents an analytical approach for the solution of the wire-tool vibration equation considering multiple spark discharges to investigate into the characteristic effects of wire vibration in Wire-cut EDM. It includes the output of the model depicting the influence of the pulse discharge frequencies under various wire tensions on the maximum amplitude of wire vibration. Also, the trend of variation of the maximum amplitude of the wire vibration with the ratio of ‘the height of a job’ to ‘the span of the wire between the guides’ has been studied.

J. Wang, B. Ravani [18] develops a computational method for numerical control (NC) of travelling wire electric discharge machining (EDM) operation from geometric representation of a desired cut profile in terms of its contours. Normalized arc length parameterization of the contour curves is used to represent the cut profile and a subdivision algorithm is developed together with kinematic analysis to generate the required motions of the machine tool axes. In generating the tool motions for cutting sections with high curvatures such as corners with small radii, a geometric path lifting method is presented that increases the machining gap and prevents gauging or wire breakage.

Y.S. Liao , Y.P. Yu [19] studied the specific discharge energy(SDE) in Wire-cut EDM. They reveal that the relative relationship of specific discharge energy (SDE) between different materials is invariant as long as all materials are machined under the same machining conditions. Discharge on time (µs), Discharge off time (µs), Arc on-time (µs), Arc off time (µs), Servo voltage (V) are taken as process parameter on a flushing type 5-axis CNC wire electrical discharge machine manufactured by Ching- Hong Inc., Taiwan with 0.25mm brass wire electrode on two different materials which are SKD11 and Inconel 718. They found that the materials having closer value of specific discharge energy (SDE) demonstrate very similar machining characteristics such as machining speed, discharge frequency, groove width and surface finish of the machined surface under the same machining conditions considering other parameters constant. The results which they derived can be applied for the determination of the settings of machining parameters of different materials. They seen that the material removal is increased but the efficiency of material removal (i.e. volume of material removal per unit energy input) is decreased with the increase of discharge on time.

Under the same machining conditions, when there is a greater SDE the surface roughness will become better, and vice versa.

Biing Hwa Yan, Hsien Chung Tsai, Fuang Yuan Huang, Long Chorng Lee [20] investigate the wire-cut electrical discharge machining (Wire-cut EDM) for machining Al2O3p/6061Al composite by taking different pulse on time to explore their effects on machining performance, including the cutting speed, the width of slit and surface roughness. All experiments were performed on a FANUC W1 CNC wire-cut electrical discharge machine with 0.25mm brass wire electrode. As well as, they see the impact of wire electrode during the machining Al2O3p/6061Al composite because of its repeatedly breaking, so this work comprehensively investigates into the locations of the broken wire and the reason of wire breaking during machining. Scanning electron microscopy (SEM) is used here to elaborate the investigation with finding on the surface of surface properties. Mainly, the effect of the process parameters including wire tension, flushing rate, and wire speed of Wire-cut EDM on wire breakage is studied. The results indicate that the cutting speed (material removal rate), the surface roughness and the width of the slit of cutting test material significantly depend on volume fraction of reinforcement (Al2O3 particles).To prevent wire breakage during machining a high flushing rate and a high wire speed are required .

Scott F. Miller, Chen-C. Kao, Albert J. Shih, Jun Qu [21] investigate the cross-section with minimum thickness and compliant mechanisms. Effects of EDM process parameters, particularly the spark cycle time and spark on-time on thin cross-section of three different work piece's, the sintered Nd–Fe–B permanent magnet, grade two commercially pure Ti, and carbon–carbon bipolar plate is been studied. All Wire-cut EDM experiments are conducted on a Brother HS-5100 wire-cut EDM machine using the brass wire electrode with 0.25 mm nominal diameter. They proposed a hypothesis based on the combined thermal and electrostatic force to cause the fracture of thin-section during Wire-cut EDM.

S. S. Mahapatra & Amar Patnaik [22] optimize the wire electrical discharge machining process parameter by using "Taguchi method". By using Taguchi's parameter design, significant and non significant machining parameters affecting the performance measures are identified as discharge current, pulse duration, pulse frequency, wire speed, wire tension, and dielectric flow. They observed that a combination of factors for optimization of each performance measure is different. They established the relationship between control factors and responses like MRR, SF and kerf width are established by means of non-linear regression analysis, resulting in a valid mathematical model. They also apply genetic algorithm, which is a popular evolutionary approach to optimize the wire electrical discharge machining process with multiple objectives.

Ramakrishnan, Karunamoorthy [23] presents a study in which a multi response optimization method using Taguchi's L16 orthogonal array robust design approach is proposed for wire-cut electrical discharge machining operations. No. of experiment has been performed under different cutting conditions taking process variables as pulse on time, wire tension, delay time, wire feed speed, and ignition current intensity. They observe their effect on responses namely material removal rate, surface roughness, and wire wear ratio considered for each experiment.They found good conformational results with study.

Mu-Tian Yan, Yi-Peng Lai [24] presents a new development and application of a new fine-finish power supply in Wire-cut EDM. A transistor-controlled power supply composed of a full-bridge circuit, two snubber circuits and a pulse control circuit was designed which in combined provide the functions of anti-electrolysis, high frequency and very-low-energy pulse control. The results which indicate that's the pulse duration of discharge current can be shortened through the adjustment of capacitance in parallel with the sparking gap. High value of capacitance contributes to longer discharge duration. They seen that the Peak current increases with the increase of pulse on-time and then it contributes to an increase in thickness of recast layer. They developed fine-finish power supply not only to eliminate titanium's bluing, rusting effect and reducing micro-cracking in tungsten carbide caused by electrolysis and oxidation but also developed the system which can achieve a fine super finish as low as 0.22µm Ra.

J.A.Sanchez, J.L.Rodil, A.Herrero [25] studied the influence of cutting speed on the performance of wire cut electric discharge machining. The limitation of machining depends on factors such as workpiece, corner radius and number of finishing cuts. Cutting speed is greatly dependent on corner radius. They concluded that the corner accuracy optimization procedure must consider the errors generated by the previous cut.

Jin Yuan, Kesheng Wang, Tao Yu, Minglun Fang [26] studied a Gaussian process regression (GPR) to find a reliable multi-objective optimization to optimize the high-speed wire-cut electrical discharge machining (Wire-cut EDM-HS) process. They take process variables as mean current pulse on-time and pulse off-time and response variables as material remove rate (MRR) and Surface Roughness (SR). Their result shows that GPR models have the advantage over other regressive models in terms of model accuracy and feature scaling and probabilistic variance. Results in the regulable coefficient parameters, the experimental optimization and optional solutions show the effectiveness of controlling optimization process to acquire more reliable optimum predictive solutions.

S.F.Hsieh , S.L.Chen , H.C.Lin , M.H.Lin , S.Y.Chiou [27] investigate the the wire-cut electric discharge machining (Wire-cut EDM) characteristics of TiNiX ternary shape memory alloys (SMAs).The experimental results show that the maximum feeding rate without breakage of wire electrode of Ti35.5 Ni49.5 Zr15 and Ti50Ni49.5Cr0.5 alloys in the Wire-cut EDM process exhibits a reverse relationship with the product of the alloy’s melting temperature and thermal conductivity. The recast layer thickness for the Wire-cut EDMed TiNiX alloys decreases with growing pulse on time. The hardness of specimen near the outer surface can reach 875 and 807 Hv for Wire-cut EDMed Ti35.5Ni49.5Zr15 and Ti50Ni49.5Cr0.5 alloys, respectively.

A. Okada, Y. Uno a, M. Nakazawa a, T. Yamauchim [28] studied the evaluations of spark distribution and wire vibration in wire-cut EDM by high speed observation. Conventionally used branched electric current method for evaluating the distribution of spark location is studied. In the branched electric current method, the discharge current is supplied from two points separated with a sufficient distance, like upper and lower current feeding contacts in a Wire-cut EDM machine. Current sensor is being to measure each current and the spark location can be obtained from the ratio of the currents from the upper and the lower contacts. The spark locations were analyzed using the recorded images by a video camera, and the effects of servo voltage, pulse interval time and wire running speed on the distribution of spark location were studied. The experimental results clarify that spark distribution becomes uniform when servo voltage is high, pulse interval time is long, and wire running speed is low. So, high applicability of the method to evaluate spark location distribution was established.

Kamal Jangra, Sandeep Grover and Aman Aggarwal [29] studied the machining of WC-Co composite using grey relational analysis (GRA) is employed along with Taguchi method through wire-cut electric discharge machining process. They studied taper angle, peak current, pulse-on time, pulse-off time, wire tension and dielectric flow rate parameters effect on material removal rate (MRR) and surface roughness (SR). Through GRA, grey relational grade is used as a performance index to determine the optimal setting of process parameters for multiple machining characteristics. Analysis of variance (ANOVA) results show that the taper angle and pulse-on time are the most significant parameters affecting the multiple machining characteristics.

Goswami Amitesh, Kumar Jatinder [30] studied the machining performance of Nimonic 80a alloy which are used extensively used for the manufacturing of aero-engine components because of its high specific strength (strength to weight ratio), which is maintained at higher temperature on wire-cut EDM process. Process parameter taken as Pulse on-time (Ton), Pulse off-time (Toff), spark gap set voltage (SV) and peak current (IP) to see effect on metal removal rate and cutting rate. They investigated that cutting speed (CS) increases with an increase in pulse-on time (Ton) and peak current (IP).cutting speed (CS) decreases with an increase in pulse-off time (Toff) and spark gap set voltage (SV). Material removal rate (MRR) increases with an increase in pulse on time (Ton) and peak current (IP). Material removal rate (MRR) decreases with an increase in pulse off time (Toff) and spark gap set voltage (SV).

L. Li, Y.B. Guo, X.T. Wei, W. Li [31] studied the surface integrity characteristics in Wire-cut EDM of inconel 718 at different discharge energy. The response they seen that the EDMed surface topography shows dominant coral reef microstructures at high discharge energy, while random micro voids are dominant at low discharge energy. Surface roughness is more or less same for parallel and perpendicular wire directions, and average roughness can be significantly reduced for low discharge energy. The thick white layers are predominantly discontinuous and non-uniform at relative high discharge energy.

Also studied that, micro voids are confined within the thick white layers and no more micro cracks were found in the subsurface. The thin white layers by finish cut at low discharge energy become more continuous, uniform, and are free of micro voids. As compared to the bulk material, white layers have insignificant reduction in micro hardness due to significant thermal degradation.

2.1 Gaps in the Literature

After a comprehensive review of literature in WIRE-CUT EDM process, it is obvious that there are a number of gaps in literature which are:-

- Limited studies have been carried out on influence of coated and uncoated wire on process responses in Wire-cut EDM.
- There is little research about wire breakage during Wire-cut EDM. Moreover, the effect of process parameters on wire breakage has not been considered.

2.2 Objective of Project

The objective of this investigation is based on using of coated and uncoated wire on process responses in Wire-Cut EDM for AISI H-13 Die steel machining keeping other process parameters constant to get desired Cutting rate, surface finish and metal removal rate and to studied the wire breakage phenomenon during machining process.

CHAPTER-3

Experimental Setup and Process Parameters Selection

3.1 Introduction

This chapter deals with experimental setup and the selection of process parameters with their range. Also, discusses the response parameters and their measuring method.

3.2 Machine

The FANUC ROBOCUT α 1-iE CNC Wire-Cut EDM was used to carry out the experiments at Tool Room and Training centre, Wazirpur, Delhi. The FANUC ROBOCUT α 1-iE CNC Wire-Cut allows operator to choose input parameters and change their values even during machining.

Figure 3.1: FANUC ROBOCUT α 1-iE Wire-Cut [32].

The Wire-cut EDM machine calculates the cutting rate, and the value is displayed on the Fanuc Series 31i-WA 15-inch large LCD touch display. The machine consist of wire feeder, work pan ,X-Y Axis mechanical unit, filter , dielectric fluid tank and microcomputer based control cabinet that are shown in Figure (3.1).

Automatic Wire Feed (AWF) mechanism is there so that wires is being feed through the workpiece automatically which enables safe unmanned operation (Figure 3.2). AWF allows the continuous operation of machining because supervisor is need after installing the program in machine.

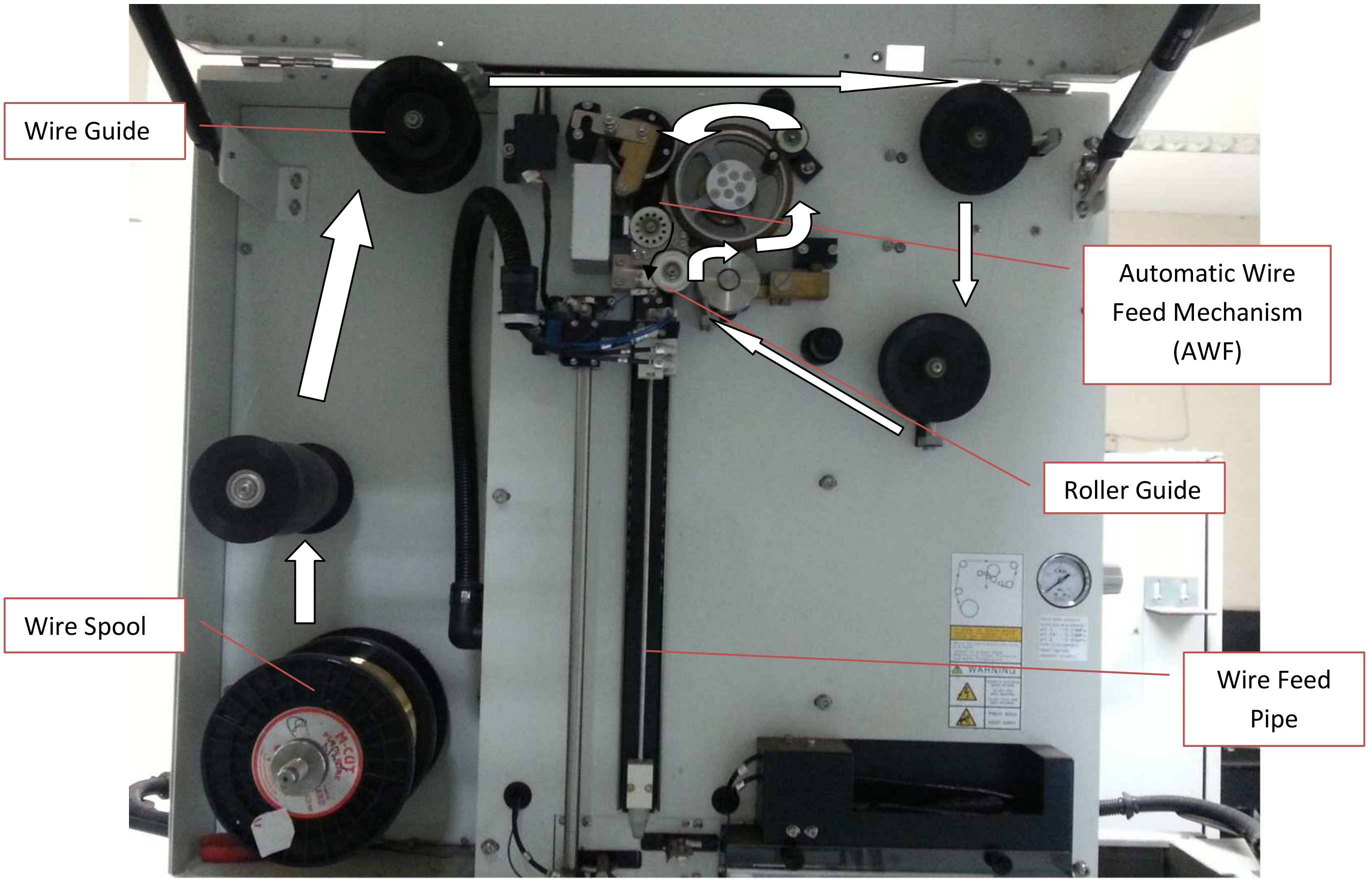


Figure 3.2: Automatic Wire Feed Mechanism

The machine has a mechanism of a wire feed through the workpiece via a hole which is already drilled into the workpiece to pass through for further cutting. For this, first wire spool is mounted on the bobbin shaft and it gets locked by a mounting nut. Then, with the help of wire guide it passes through roller which straighten the wire and automatic wire feed mechanism feed the wire into the pipe with the help of roller guide which provide tension to the wire as selected while machining and at the end, wire pipe moves down touches the upper guide pass the wire through it.

After that wire is forced with water to pass through the workpiece and at last it reaches to the lower guide.

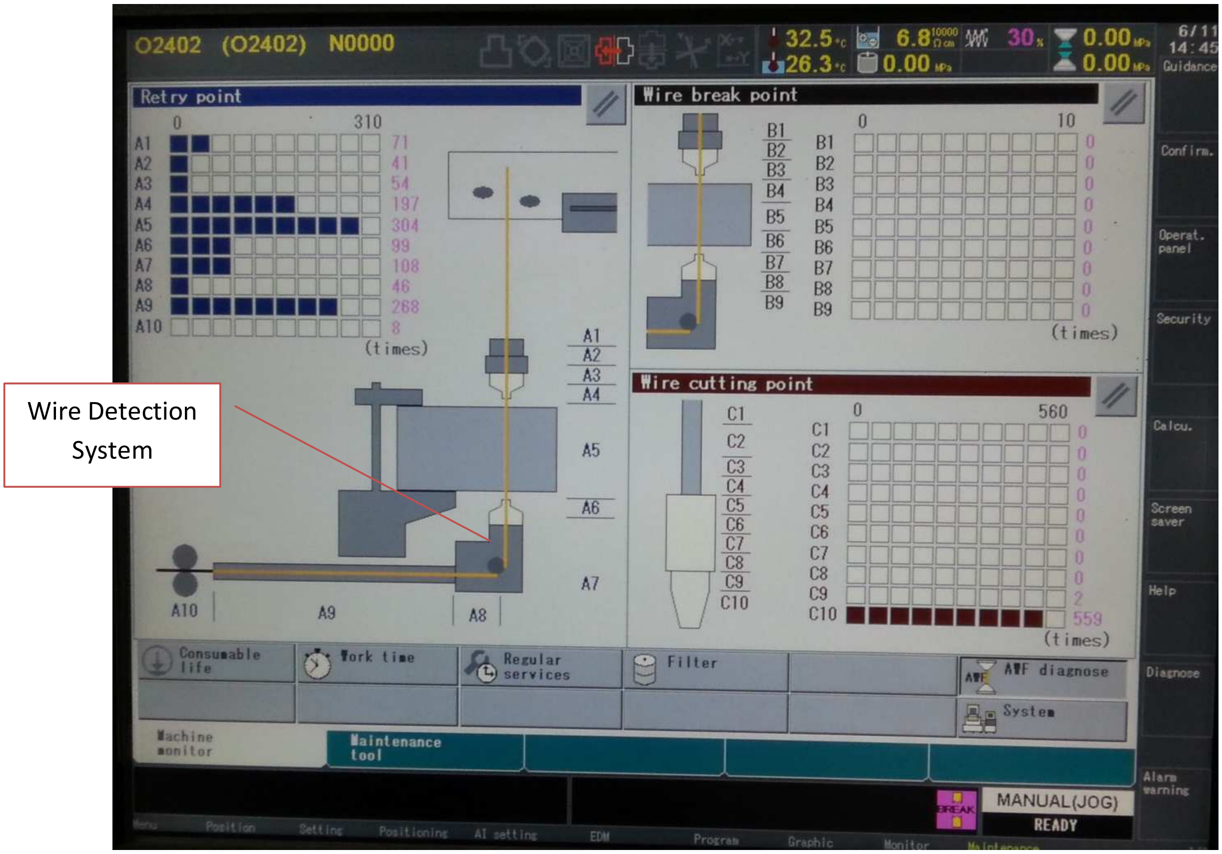


Figure 3.3: Wire Detection System

Whole process of automatic wire feeding is under supervision on the Fanuc Series 31i-WA 15-inch large LCD monitor so that user can know exactly where the wire is during the process at different stages of feeding as shown in the Figure (3.3). Machine uses different sensors to sense the positioning of wire.

Machining process cannot get started until the parameters are set. For selecting the different process parameter, moving the unit in X-Y axis, inserting the program for machining, getting feedback during machining, changing the parameters during machining, etc. for all these purposes a unique the Fanuc Series 31i-WA 15-inch large LCD monitor control panel is employed which have different section for initializing, controlling and monitoring the machining process (Figure 3.4). The Fanuc Series 31i-WA 15-inch large LCD has touch panel through which user can change the values in parameters and can see the wire cutting path on screen as well as response parameters is also shown on the screen.

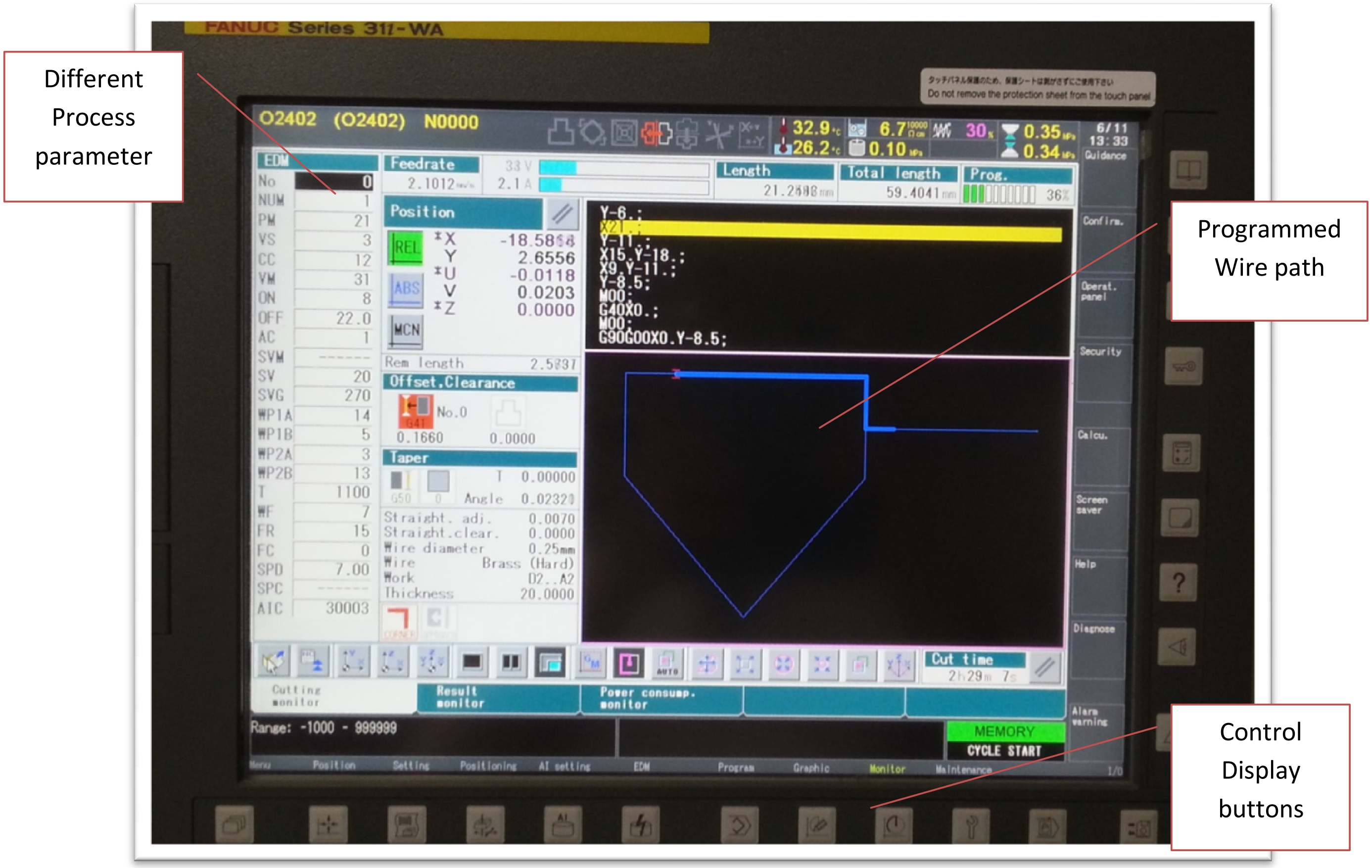


Figure 3.4: Fanuc Series 31i-WA 15-inch large LCD monitor

Various process parameter is shown on touch screen where it can altered at any time during machining also like pulse-on time, pulse-off time, wire tension, wire feed rate, servo voltage etc. and response parameters is also shown like cutting rate etc. Wire-cut machine tool has configuration as shown in Table (3.1) and dielectric fluid configuration in Table (3.2).

The ROBOCUT α 1-iE CNC Wire-Cut machine setup has following configuration.

Table 3.1: FANUC ROBOCUT Wire-Cut machine configuration [32].

Wire-Cut EDM		
Maximum Workpiece size	mm	1050 x 820 x 300
Maximum Workpiece Weight	Kg	1000
Table travel (X&Y Axes)	mm	600 x 400
U & V Axis Travels	mm	±100 x ±100
Z Axis Travels	mm	310
Auto-Wire Feed (AWF)	_	Standard
Wire Diameter	mm (Ø)	0.1- 0.3
Maximum Wire Spool Weight	Kg	16
Wire Tension	Grams	200-2500
Machine Weight	Kg	3000
Fanuc 31i-WA touch Screen control	mm	386
Maximum Programming Memory	megabyte	4 mb

Table 3.2: Dielectric Fluid of Wire-cut EDM [32].

Dielectric Tank (Demineralised water)		
Tank Capacity	Litres	800
Paper Filter	Quantity	2
Deionizer	Cubic feet	1
Inverter chiller	_	Standard

Table 3.3: Power supply of machine tool [32].

Power Supply		
Digital Power Supply	-	standard
AC Power Supply	Switchable	AC/DC
Pulse Generator	Transistor Driven	Standard
Input/output Supply	3 Phase 60 Hz	200/220
	KVA	13

3.3 Workpiece Material

AISI H-13 is been used as workpiece material for present investigation. AISI H-13 is special hot-worked chromium tool die-steel with good hardness and toughness properties. Tool steels are used to construct the die components subject to wear. It is used for extreme load conditions such as hot-work forging, extrusion etc. as well as in a variety of press-working operations. These steels are designed especially to develop high hardness levels and abrasion resistance during operation (Table 3.4).

AISI H-13 hot working die steel has been used in various fields like manufacturing of punching tools, mandrels, mechanical press forging die, plastic mould and die-casting dies, aircraft landing gears, helicopter rotor blades and shafts. The working life and dimensional accuracy of AISI H-13 steel dies and tools can be improved with suitable heat treatment (Figure 3.5).

Table 3.4: Mechanical Properties of AISI H-13 die steel [33].

Density (@20ºC)	7861 kg/m^3
Melting Point	1427ºC)
Tensile strength, ultimate (@20ºC)	1200-1590 Mpa
Modulus of elasticity (@20°C)	215 Gpa
Poisson’s ratio	0.27-0.30

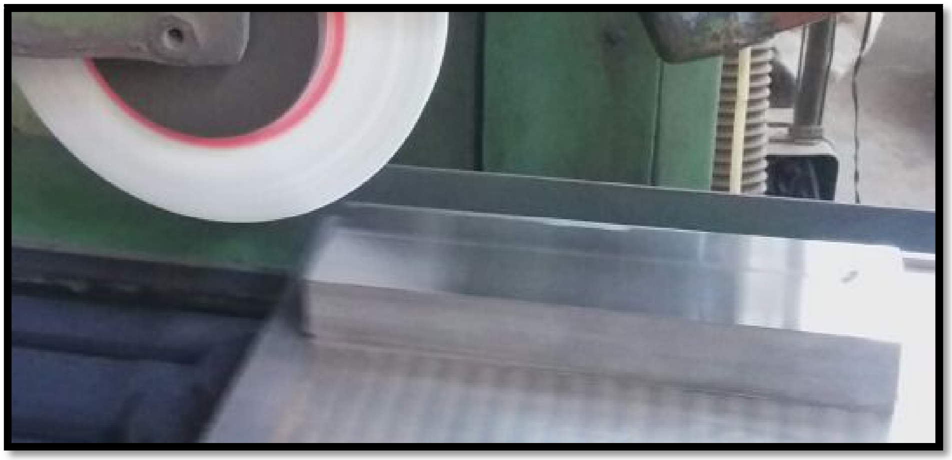


Figure 3.5: H-13 Die steel workpiece before machining

Pie-chart shows the composition of the AISI H-13 Die Steel with a significant contribution of carbon (0.356 %), Silicon (0.885%), Chromium (5.109%), molybdenum (1.220%) etc. (Figure 3.6).

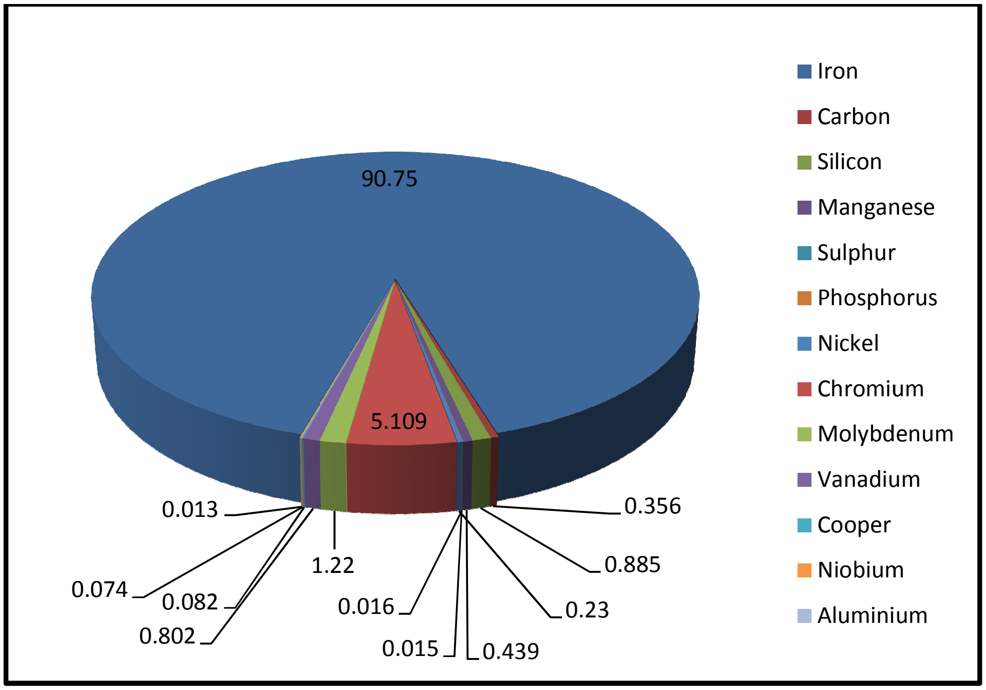


Figure 3.6: Spectroscopy analysis of AISI H-13 Die Steel in percentage

A spectroscopy analysis has been done on workpiece AISI H-13 die steel shows the following result which confined the workpiece material to AISI H-13 Die steel specifications (Table 3.5).

Table 3.5: Chemical Composition of Workpiece Material in percentage

Fe	C	Si	Mn	P	S	Cr	Mo	V
90.750	0.356	0.885	0.439	0.015	0.016	5.109	1.220	0.802

AISI H-13 die steel has the following advantages:-

1. Good resistance to thermal fatigue.
2. Superior properties at elevated temperatures.
3. Excellent impact strength.
4. Deep hardening.

3.4 Wire Electrodes

In Wire-cut EDM process, a thin single-strand metal wire (usually brass) is fed through the work piece submerged in a tank of dielectric fluid, through which sparks are discharged to erode the work piece material.

Wire-cut EDM processes have the following performance parameter:-

1. High cutting speed.
2. Resistance against wire rupture.
3. Accurate machining to improve productivity.
4. Achieve high quality in machining.

There are several factors which have effect on process of Wire-Cut EDM process, such as electrical parameters, wire electrode material, angle of taper, work piece height, long period of unattended operation, choosing an optimum wire is significant critical factor.

The wire electrode used in Wire-cut EDM 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. According to that wire electrode should have following properties.

1. The high **electrical conductivity** helps the wire transfers energy to workpiece efficiently and minimize energy loss of sparking during machining.
2. The wire with **high tensile strength** is a good heat resistance in high temperature and maintains straight under vibration and tension.
3. The **low melting temperature** of wire improves the spark formation and decrease dielectric ionization time.
4. The **higher thermal conductivity** of the electrode ensures a better spark discharge energy distribution during the Wire-cut EDM process. This will increase material removal rate.

Considering the above factors we have chosen a **hard brass wire** (uncoated wire) and **zinc coated brass wire** (coated wire) for carrying out experiments (Table 3.6).

Table 3.6: Wire Electrode Specification

Wire Electrode	Hard Brass wire	Zinc coated wire
Material	Cu-Zn core wire	65/35 % Core Composition with Zinc Coating
Tensile Strength	140,000 PSI	132,000 PSI
Wire Diameter	0.25Ø	0.25Ø
Price	Rs 550/kg	Rs 650/kg

Brass wire electrode is a successor of cooper wire and it is still commonly used wire today. Brass which is an alloy copper and zinc provides a powerful combination of low cost, reasonable conductivity, high tensile strength and improved fusibility.

Zinc coated brass wire electrode was one of the first attempts to present more zinc to the wire’s surface. This wire consists of a layer (approx.5 micron) zinc coating over a core which is one of the standard EDM brass alloy. Then this wire provides a significant increase in cutting rate over a brass wire, without any sacrifice in any other critical properties.

3.5 Selection of Process Parameter

The process parameters that may affect the machining characteristics of Wire-cut EDM machined parts .Some of the parameters are fixed in all experiments to avoid any bias in results. Therefore, selection of process parameter is very important .They is as follows:-

3.5.1 Pulse-on Time

The pulse-on time is referred as Ton and it represents the duration of time in milliseconds, ms, for which the current is flowing in each cycle. Machining is going to be done during this period. During this time the voltage is applied across the electrodes. A range of pulse on time available on the machine is 1-20 in steps of 1mu.

Increasing pulse duration results in higher cutting rate because the single pulse discharge energy increases. A higher Ton results in the broader and deeper craters will be produced that results in smoother surface. Also, higher pulse duration leads to wire breakage during machining.

3.5.2 Pulse-off Time

The pulse-off time is referred as Toff and it represents the duration of time in milliseconds, ms, between the two simultaneous sparks. In time between two pulses, the pulse rests and re-ionization of the dielectric take place since the machining take places during one pulse duration. The voltage is absent during this part of the cycle. The time between two pulses, Toff setting time range available on the machine tool is 6-200 mu.

The sparking efficiency increases with a lower value of Toff due to more number of discharges in a given time. It results, the cutting rate gets increase. Too short time between two pulses leads to wire breakage frequently and surface roughness will increases.

3.5.3 Wire Feed Rate

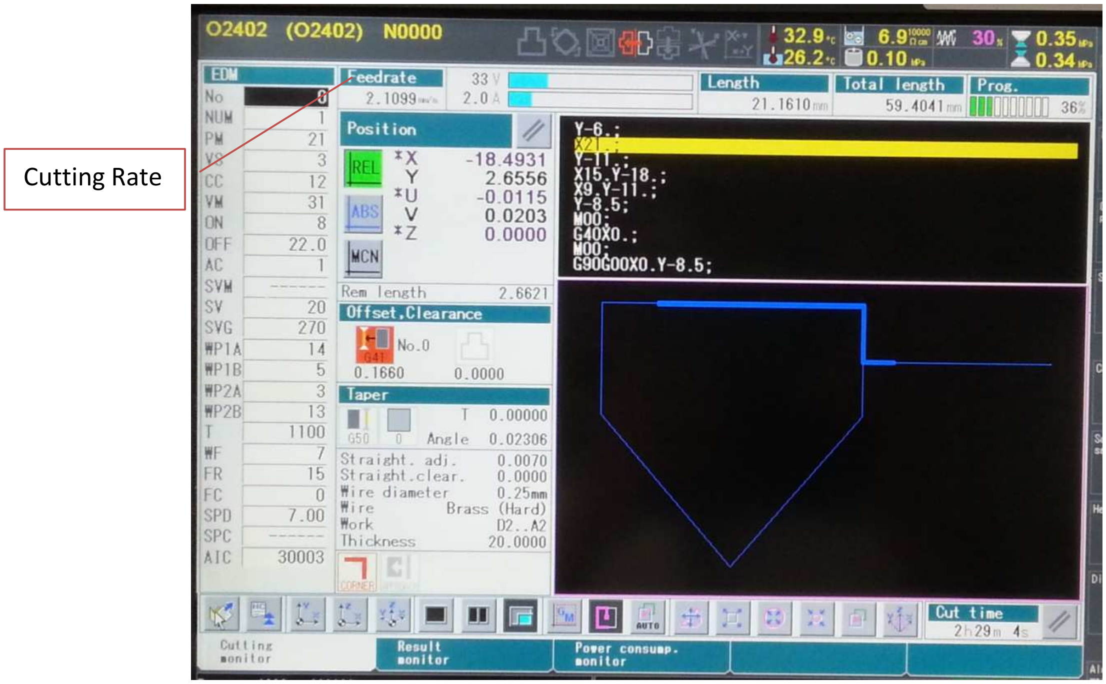
Wire feed rate is the rate at which the wire-electrode travels along the wire guide path and is fed continuously for sparking. The wire feed rate range available on the machine is 1-15 (m/min.) It is always desirable to set the wire feed rate to maximum to achieve in less wire breakage, better machining stability and slightly more cutting rate.

3.5.4 Wire Tension

Wire tension determines how much the wire is to be stretched 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 0-2500 (gm).

3.6 Measurement of Process Output Responses

Cutting rate, Surface Roughness and Metal removal rate were considered as output responses of Wire-cut EDM process and are presented in the following subsections.


Cutting Rate

O2402 (O2402) N0000

EDM	
No	0
NUM	1
PM	21
VS	3
CC	12
VM	31
ON	8
OFF	22.0
AC	1
SVM	-------
SV	20
SVG	270
WP1A	14
WP1B	5
WP2A	3
WP2B	13
T	1100
WF	7
FR	15
FC	0
SPD	7.00
SPC	-------
AIC	30003

Feedrate 2.1099 mm/s
33 V
2.0 A

Length 21.1610 mm
Total length 59.4041 mm
Prog. 36%

Position
*X -18.4931
Y 2.6556
*U -0.0115
V 0.0203
*Z 0.0000

Rem length 2.6621

Offset,Clearance
No.0
0.1660 0.0000

Taper
T 0.00000
Angle 0.02306

Straight. adj. 0.0070
Straight.clear. 0.0000
Wire diameter 0.25mm
Wire Brass (Hard)
Work D2..A2
Thickness 20.0000

```
Y-6.;
X21.;
Y-11.;
X15.Y-18.;
X9.Y-11.;
Y-8.5;
M00;
G40X0.;
M00;
G90G00X0.Y-8.5;
```

Cut time 2h29m 4s

Figure 3.7: Cutting Rate Display on Screen

3.6.1 Cutting Rate

For Wire-cut EDM, large cutting rate is a desirable characteristic and high productivity of Wire-cut EDM achieved with maximum amount of cutting rate. To measure the material removal rate during machining, a straight line cut is there in the work piece. When the wire had made approximately 50% of this straight line cut, the steady cutting rate value was read off the display monitor as shown as in Figure (3.7). Also, Demineralised water was selected as the dielectric for experiments, as that is the standard for Wire-cut EDM.

3.6.2 Surface Roughness

One of a good predictor of Wire-cut 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. The parameter used for general surface roughness is Ra (µm).Ra is the universally recognises and most used international parameter.

$$R_a = \frac{1}{l}\int_0^1 |Z(x)| dx$$

It calculates average roughness by comparing all the peaks and valleys on the surface to the mean line of roughness, and then it averaging them all over the entire cut-off length. If these deviations are large, the surface is rough; if small, the surface is smooth.

Figure 3.8: Taylor-Hobson Surface Roughness Testers

In this study, Taylor-Hobson Surtronic3+ surface roughness tester (Figure 3.8) is being used for calculating the surface roughness of workpiece specimens. Here, Cut-off length is 2.5mm. The cut-off length is a significant part for surface roughness measurement. Cut-off length determines the accuracy of the results.

A longer cut-off length will give a more accurate average value, and a shorter cut-off length might give a less accurate result over a shorter stretch of surface. A Diamond inserted stylus has been used in tester to increase the accuracy of study as shown in Figure (3.9).

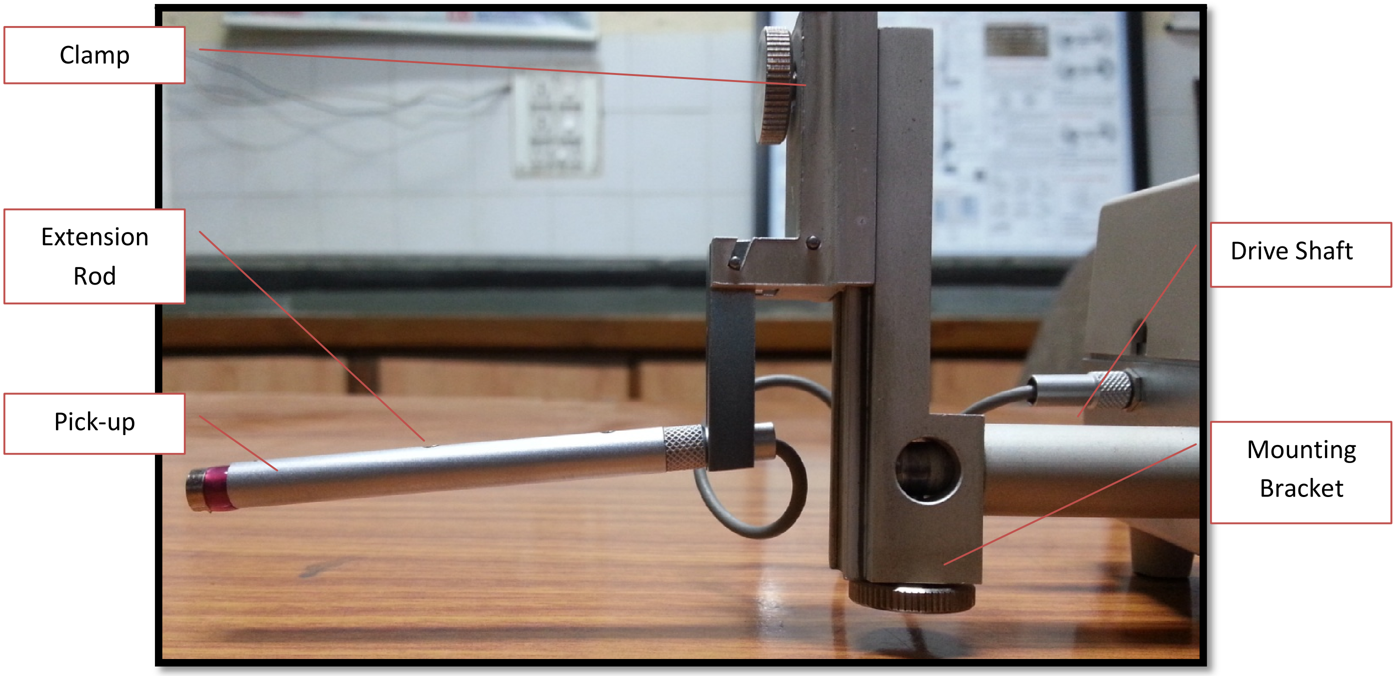


Figure 3.9: Taylor-Hobson Surtronic3+ Stylus

3.6.3 Metal Removal Rate

The material removal rate is one of the desirable characteristics and it should be higher to increase the productivity to reduce machining cycle time. It refers to the volume of material removed from the work piece per unit time. In the present study, MRR was calculated as mm^3/min.

The thickness of the workpiece material is 31 mm. In Wire-cut EDM operations, material removal rate (MRR) is a significant factor to determine economics of machining and rate of production. Material removal rate is a rate at which the volumetric material is being removed from the work-piece specimen in Wire-cut EDM machine. Here, the effects of the machining parameters on the MRR have also been considered as measure of the machining performance.

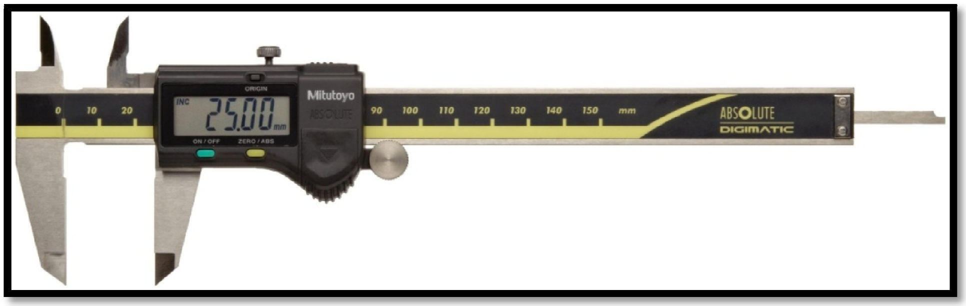


Figure 3.10: Mitutoyo Digital Vernier Caliper

The Metal removal rate is calculated as:-

$$MRR = V_c . b. h \text{ (mm}^3\text{/min)} \qquad [34]$$

Where, V_c = cutting rate, mm/min;
b =width of cut, mm;
h= height of the work piece, mm.

3.7 Workpiece Preparation

Preparations of workpiece for the experimental purpose consist of many phases through which the workpiece has been gone through. A plate which is roughly cuboid in shape is been cut from a big block of AISI H-13 Die Steel. Preparation of workpiece is itself important because it make quite helpful in holding and clamping the workpiece on the wire-cut edm machine.

Then, this roughly cuboid plate is being machined on milling machine (Figure 3.11) so it becomes a complete cuboid with 210mm x 70mm x 31mm plate as shown in the figure. After that, it goes on grinding machine (Figure 3.12) where it is been grind to remove all inaccuracies in the workpiece so that it become ready for machining on Wire-cut Edm machine. The desired dimension of our cut piece is 12mm x12mm x31mm having a shape as shown in Figure.

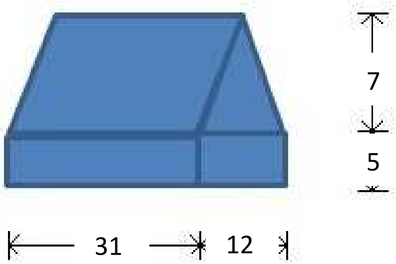


Figure 3.11: Workpiece Dimension.

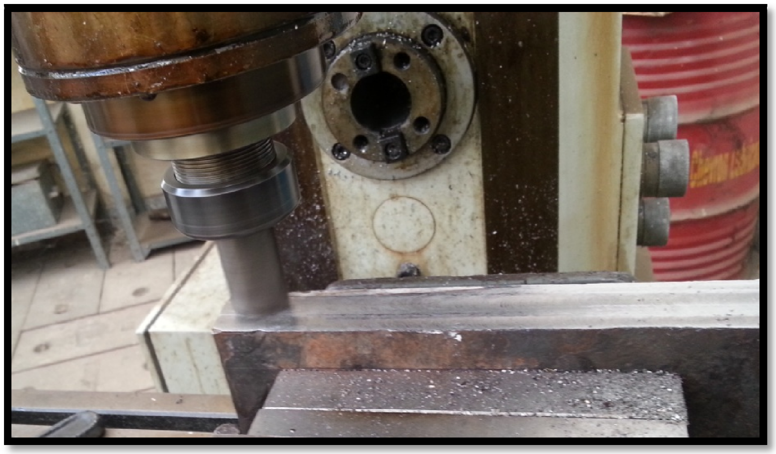


Figure 3.12: Milling Process on Workpiece

Figure 3.13: Grinding process on workpiece

A dial indicator has been used to make it parallel in all three directions to the machine tool workpiece table, so that workpiece surfaces is been parallel to all moving directions and taper can be avoided.

CHAPTER 4

Design and Experimental Approach

4.1 Introduction

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 unbiased valid and objective conclusions. Thus, there are two aspects of an experimental problem: the Design Of Experiments (DOE) and the statistical analysis of the data.

Design Of Experiment (DOE) is powerful statistical tool introduced by R.A. Fisher in England in the early 1920 to study the effect of different factors affecting the mean and variance of process performance characteristics. 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 achieved.
- 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 Analysis of Variance (ANOVA) have been used to plan the experiments and subsequent analysis of the data collected.

4.2 Taguchi Experimental Design Method and Analysis

4.2.1 Taguchi's Philosophy

Taguchi has envisaged a new method of conducting the design of experiments which are based on well defined guidelines. This method uses a special set of arrays called orthogonal arrays. These standard arrays stipulate the way of conducting the minimal number of experiments which could give the full information of all the factors that affect the performance parameter. The crux of the orthogonal arrays method lies in choosing the level combinations of the input design variables for each experiment. This philosophy was first applied in Ford Motor Company to train the skill engineers for quality improvement. It was based on three simple and fundamental concepts:-

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

Taguchi's also observes that poor quality cannot be improved by the process of inspection, screening and salvaging of the product. No amount of any inspection can put quality back into the product. For this, Taguchi recommends a three-stage process: a system design, a parameter design and a tolerance design to make a considerable effect on the process [35].

In the present study, Taguchi's parameter design approach is used to study the effect of process parameters on the various responses of the Wire-cut EDM machining on the AISI H-13 Die Steel workpiece material.

4.2.2 Experimental Design Strategy

Taguchi recommends Orthogonal Array (OA) for lying out of experiments. These orthogonal arrays 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 traditional full factorial design has the disadvantage of including all the possible combination setting of the parameters involved in the study which is tedious in nature, resulting in a very large number of experiments and considerable time resource is required to accomplish the task. In fractional factorial Design Of Experiments (DOE), only a small fraction of settings from all possible combination is selected, which reduces the number of tests to a reasonable level for that process [36].

The design of experiments using the orthogonal array is, in most cases, efficient when compared to many other statistical designs. The minimum number of experiments that are required to conduct the Taguchi method can be calculated based on the degrees of freedom approach.

$$N_{Taguchi} = 1 + \sum_{i=1}^{NV} L_I - 1$$

4.3 Designing an Experiment

The Design of Experiment (DOE) is an essential part of the investigation and to conduct the experiments in a right manner considering the various parameters whether they are variable or fixed throughout the study.

The design of an experiment involves the following steps:-

1. Selection of independent variables in the process.
2. Selection of number of level settings for each independent parameter.
3. Selection of orthogonal array according to factors and levels.
4. Assigning the independent variables to each column.
5. Conducting the experiments with trials.
6. Analyzing the data with a statistical analyzer.
7. Inference.

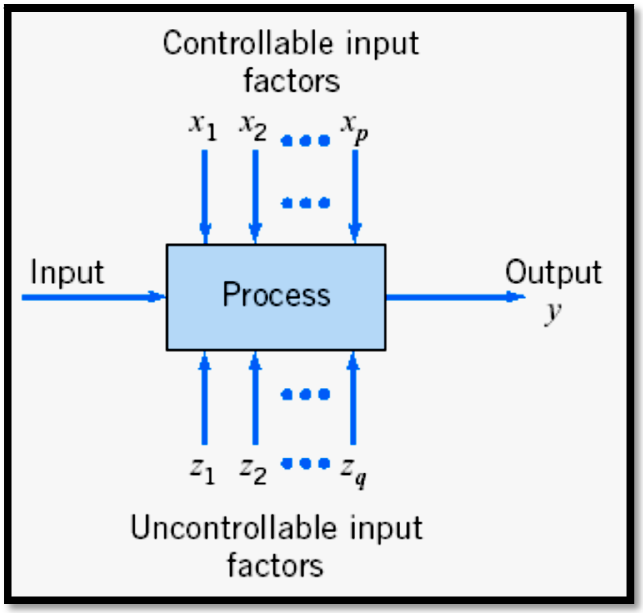


Figure 4.1: General model of a process or system [37].

The designed experiments are the test or series of tests in which purposeful changes are made to the input process variables of a process or system so that we can observe and identify the reasons for changes in the output response variables (Figure 4.1). There are always some factors which are controllable and uncontrollable in nature which may affect the output response variables, we also have to keep eye on uncontrollable factors to make their effects nullify.

4.3.1 Parameters Selection

Selecting the input process parameters and response parameters has to be determined before performing the experiments. In this study, the behaviours of four control factors were studied. These parameters with their levels are listed in Table 4.1.

Process parameters must be at least in three levels to reflect the true behaviour of output parameters of study the machining parameters were chosen based on review of the literature and experience, level of each parameter is taken by considering the constraints on the range according to the Fanuc Robocut Wire-cut CNC machine tool manual.

Table 4.1: Machining parameters and their levels

Process Parameter	Symbol	Units	Level 1	Level 2	Level 3
Pulse-on Time	Ton	µs	8	16	24
Pulse-off Time	Toff	µs	50	100	150
Wire Tension	T	gm	900	1400	1900
Wire Feed Rate	W	m/min	8	10	12

The Wire-cut EDM experiment was performed in order to study the effect of process parameters on the output response characteristics such as Metal removal rate, cutting speed and surface roughness. High productivity of Wire-cut EDM is achieved with maximum amount of cutting rate & metal removal rate and minimum amount of surface roughness.

Table 4.2 and Table 4.3 shows the selected L9 orthogonal array in matrix form with coded values and with process parameter value respectively.

Table 4.2: L9 Orthogonal Array Layout in coded form

Process Parameter					**Response**	
Expt. No.	**Ton**	**Toff**	**T**	**W**	**R1**	**R2**
1	1	1	1	1		
2	1	2	2	2		
3	1	3	3	3		
4	2	1	2	3		
5	2	2	3	1		
6	2	3	1	2		
7	3	1	3	2		
8	3	2	1	3		
9	3	3	2	1		

The S/N ratio and average value of the response characteristics for each variable at different levels were calculated from experimental data. Each three level parameter has two degree of freedom (number of levels – 1), the total “degree of freedom” required for four variables each at three levels is 8 (i.e. 4× (3–1)). As per Taguchi’s method the total “degree of freedom” of selected orthogonal array must be greater than or equal to the total “degree of freedom” required for the experiment. So a, L9 orthogonal array (a standard three-level OA) with 8 “degree of freedom” was selected for the present study.

Table 4.3: L9 Orthogonal Array Layout with process parameter

Process Parameter					**Response**	
Expt. No.	**Ton**	**Toff**	**T**	**W**	**R1**	**R2**
1	8	50	900	8		
2	8	100	1400	10		
3	8	150	1900	12		
4	16	50	1400	12		
5	16	100	1900	8		
6	16	150	900	10		
7	24	50	1900	10		
8	24	100	900	12		
9	24	150	1400	8		

4.4 Loss Function and S/N Ratio

Taguchi defines the loss function as in which loss function is proportional to the deviation from the target quality characteristic. At zero deviation, performance is focused on the target and the loss is zero. The loss function is linked with the quality matrix of the system. The loss associated with the process of product can be minimized by maximizing the S/N ratio. The main goal of Taguchi method was to reduce the manufacturing cost from inconsistency in manufacturing processes. As defined by Taguchi the difference between the actual value of the characteristic (Y) and target value of the performance characteristic (T) as a loss function as shown bellow;

$$L(Y) = K(Y-T)^{2}$$

Where L= loss in monitory unit, T = target value of the performance characteristic, Y= actual value of the characteristic, K= constant depending upon the magnitude of the characteristic and the monitory units involved. The graphical representation of loss function is shown in Figure (4.2).

The average loss per unit in a mass production process is expressed as:

$$L(Y) = K(Y1-T)^{2} + K(Y2-T)^{2} + \ldots\ldots\ldots\ldots\ldots\ldots.. K(Yn-T)^{2}$$

Where Y1, Y2, Y3……….Yn = Characteristic values for units 1, 2, 3 …n respectively.

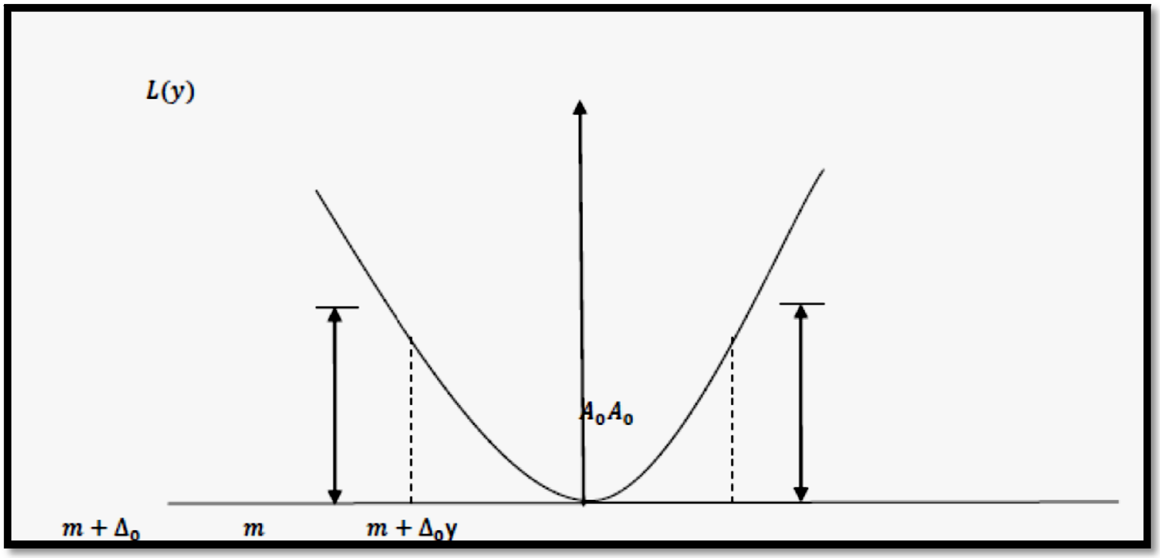


Figure 4.2: Taguchi Loss Function [35].

K = Constant depending upon the magnitude of characteristic, T=Target value. Loss function was transformed into a concurrent statics called S/N ratio, which combines both the mean value and the variance around the mean. The S/N ratio provides a measure of the impact of noise factors on the performance. The larger the S/N ratio, the more robust the product is against the noise. Three types of the S/N ratios are employed in practice depending upon the experimental objective and the type of response .The signal to noise ratios(S/N) in terms of larger the better (LB), smaller the better (SB) and nominal the best (NB) are calculated by using the following equations.

1. Larger the better
LB: S/N Ratio = $-10\log10\ [(1/N)^{*}\ \Sigma(1/Yi^{2})]$

2. Smaller the better
SB: S/N Ratio = $-10\log10\ [(1/N)^{*}\ \Sigma(Yi^{2})]$

3. Nominal the better
NB: S/N Ratio = $-10\log10\ [\text{Mean}^{2}/\text{variance}]$

Where Yi is the performance characteristic and N is the number of observations for each trail. For the "nominal is best" characteristic, the standard definition of target 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 target is being sought.

4.5 Experimentation and data collection

The experiment is performed against each no 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 any bias in the experiment result. The data (raw data) are recorded against each no trial condition and S/N ratios of the repeated data points are calculated and recorded against each no trial condition.

4.6 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 [35]. However, in the present investigation the following methods have been used:

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

The plot of average responses at each level of a parameter indicates the trend in results. It is a pictorial representation of the effect of parameter on the response parameter. The change in the response parameter with the change in levels of a parameter can easily be determined from these plots. Typically, ANOVA for OA's are conducted in the same manner as other structured experiments.

The S/N ratio is treated as a response of the investigation, 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 process parameters.

4.7 General Linear Regression Analysis

The purpose of developing the statistical model relating the response parameters and their process parameters was to facilitate the optimization of machining new and advanced engineering materials, ceramic materials and MMCs in Wire-cut EDM and to achieve higher MRR, cutting rate with a desired accuracy and surface finish. However, the selection of cutting parameters for obtaining the higher cutting efficiency or accuracy in Wire-cut EDM is still not fully achieved, even with the most up-to date CNC Wire-cut EDM machine tool. This is mainly due to the nature of the complicated stochastic process mechanisms in wire-cut EDM process. As a result, the relationships between the process parameters and the response parameter are hard to model accurately and efficiently.

Many researchers have successfully used General Regression analysis method to obtain the mathematical relations between machining response parameters and machining process parameters. Minitab 16.2.4 software is used to analysis the regression model. In this research, General linear regression analysis was used to establish a mathematical model between the experimentally obtained machining outputs and machining parameters of Wire-cut EDM by Minitab software.

1) Cutting rate = 35.7495 + 0.829708*(Pulse-on time) - 0.0214733*(Pulse-off time) + 0.00325233*(Wire Tension) + 0.026 (Wire Feedrate).

2) Surface roughness = 1.86917 + 0.046875*(Pulse-on time) - 0.00035*(Pulse-off time) + 0.0002 *(Wire Tension) + 0.02125*(Wire Feedrate).

3) Metal removal rate = 8.83541 + 0.351143*(Pulse-on Time)+ 0.0220612*(Pulse-off Time) + 0.00153717*(Wire Tension) + 0.0892732*(Wire Feedrate)

General linear regression analysis is a collection of mathematical and statistical techniques that are useful for modelling and analysis of problem in which a response of interest is influenced by several variables and the objective is to optimize these responses. General linear regression analysis allows for better understanding of relations between inputs and responses. In this study, Wire-cut EDM process parameters refer pulse-on time, pulse-off time, wire feed rate, wire tension and the responses are material removal rate, surface roughness and cutting rate.

CHAPTER 5

Experimental Results and Analysis of Taguchi Design Method

5.1 Introduction

The objective of the experiments was to investigate the effect of process parameters on Wire-cut EDM performance e.g. cutting rate, surface roughness, wire rupture and surface integrity. The experimental results are discussed subsequently in the following sections.

5.2 Experimental Results

The Wire-cut EDM experiments were performed in order to study the effect of process parameters on the output response characteristics with the process parameters as given earlier. The experimental results are collected for metal removal rate, cutting rate and surface roughness. Nine Experiments were conducted using Taguchi experimental design method and there were two replicates for each experiment to obtain S/N values [38]. In this study all the designs, plots and analysis were carried out using Minitab 16.2.4 statistical software.

Larger cutting rate amount, larger metal removal rate and lower amount of surface roughness show the high quality and productivity of Wire-cut EDM. Therefore, “Larger the better” formula is applied to calculate the S/N ratio of cutting rate and metal removal rate and “Small the better” formula is applied to calculate the S/N ratio surface roughness.

5.2.1 Effect on Cutting Rate

Experiments were conducted using L9 OA to find the effect of process parameters on the cutting rate response parameter. The experiments were done on AISI H-13 high chromium Die steel. Zinc coated wire and bare brass wire were used as electrode tools. The rate of cutting rate for each workpiece and tool materials were collected in desired experimental conditions. First, the response table for S/N ratio and mean shows the importance and contribution of each significant parameter on cutting rate, metal removal rate and surface roughness. At the end, ANOVA table was carried out for all process parameters to determine the significant ones.

5.2.1.1 Zinc Coated Wire on AISI H-13 Die steel

Zinc coated wire-electrode is being used with AISI H-13 die steel workpiece to study the effect of cutting rate on machining with Wire-cut EDM.

Table 5.1: Experimental results of cutting rate for zinc coated wire

Exp. No.	**Cutting Rate (mm/hr)**		**S/N Ratio**
	R1	**R2**	
1	62.526	62.388	35.91
2	67.716	67.968	36.63
3	65.370	65.712	36.33
4	80.472	80.352	38.11
5	77.988	78.576	37.87
6	74.946	75.012	37.50
7	91.868	92.296	39.28
8	83.598	83.826	38.46
9	85.884	86.790	38.72

Minitab statistical software 16.2.4 package has been used to calculate S/N ratio to analyze the experimental result. Minitab software assigns ranks based on delta values which is difference is the highest average minus the lowest average for each factor in descending order; the highest delta value has ranked 1 and ranked 2 is assigned to the second highest, and so on to other parameters. The ranks indicate the relative importance of each factor to the response.

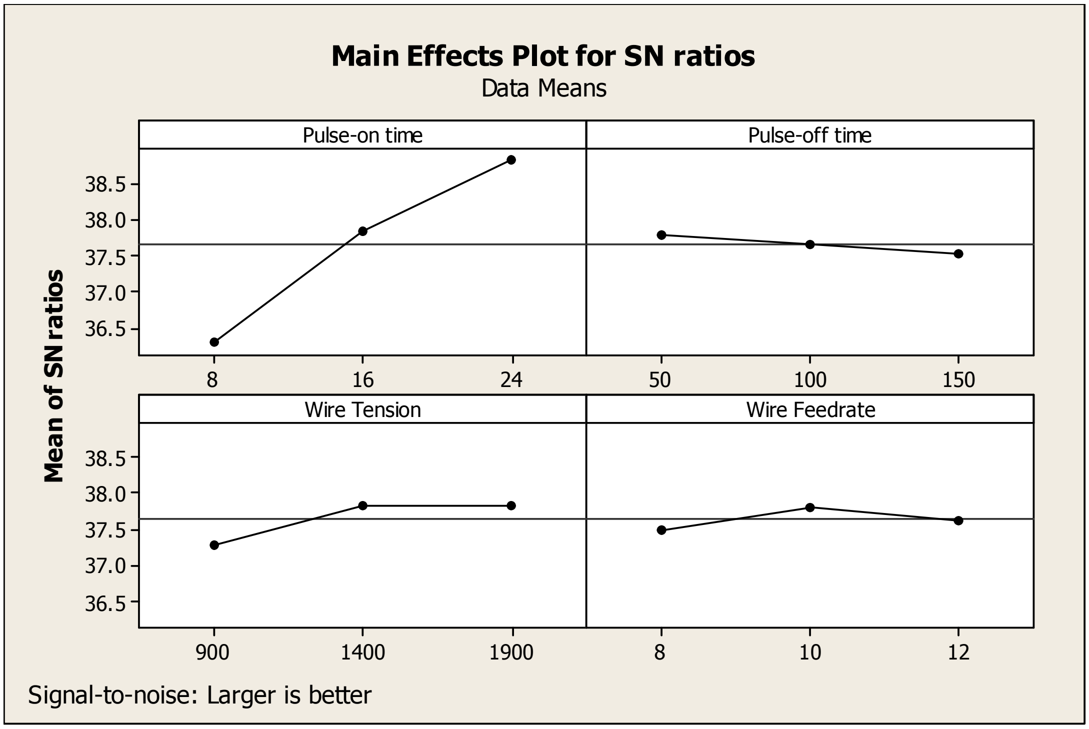


Figure 5.1: Effect of process parameter on cutting rate with zinc coated wire (S/N ratio)

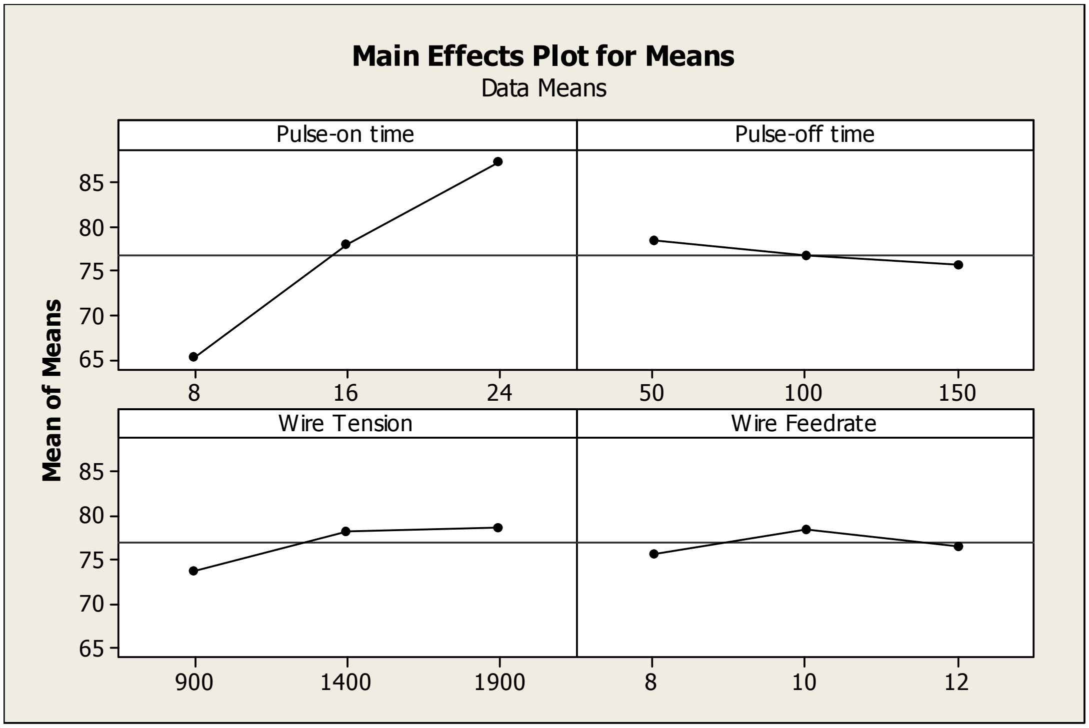


Figure 5.2: Effect of process parameter on cutting rate with zinc coated wire (Raw Data)

Cutting rate should be large as much as possible. So, for that Minitab software is being set for "Larger the Better" mode to find out the levels at which maximum cutting rate is being achieved.

Figure (5.1) & (5.2) shows that the third level of Pulse-on time (Ton_3), the first level of Pulse-off time ($Toff_1$), third level Wire tension (T_3) and Second level of Wire Feedrate (W_2) provide the maximum value of cutting rate. The same levels of the parameters (Ton_3, $Toff_1$, T_3 and W_2) are the best levels for the maximum cutting rate in Wire-cut EDM process are achieved by raw data analysis.

Table 5.2: Response Table for S/N Ratios of cutting rate with zinc coated wire

Level	Pulse-on Time	Pulse-off Time	Wire Tension	Wire Feedrate
1	36.29	37.77	37.29	37.50
2	37.83	37.65	37.82	37.80
3	38.82	37.52	37.83	37.63
Delta	2.53	0.25	0.54	0.30
Rank	1	4	2	3

Response table for S/N ratio provided by Minitab considering delta statistics shows that Pulse-on time has maximum contribution followed by wire tension, wire feedrate and pulse-off time respectively for maximum cutting rate as they ranked 1, 2, 3 and 4 respectively.

Table 5.3: Analysis of Variance for S/N ratio of cutting rate with zinc coated wire

Parameters	**Degrees of Freedom**	**Sum of Squares**	**Mean Square**	**F-factor**	**Factor Effect (percent contribution)**	**Optimum Level**
Pulse-on Time	2	9.7501	4.8751	46.1867	92.3733	Ton_3
Pulse-off Time	2	0.0937	0.0468	0.4439	0.8877	-
Wire Tension	2	0.5741	0.2871	2.7196	5.4392	T_3
Wire Feedrate	2	0.1372	0.0686	0.6499	1.2998	-
Total	8	10.5551	5.2776		100.0000	

In order to find the significance of the process parameters towards cutting rate ANOVA table was established. Form the table of ANOVA (analysis of variance) for the S/N ratio it was concluded that both Pulse-on time and Wire tension significantly affects the variation in the cutting rate values. It is also evident that Pulse-off time and Wire feedrate are non-significant process parameters for cutting rate. Optimum levels for Pulse-on time and Wire Tension are (Ton_3) and (T_3) respectively.

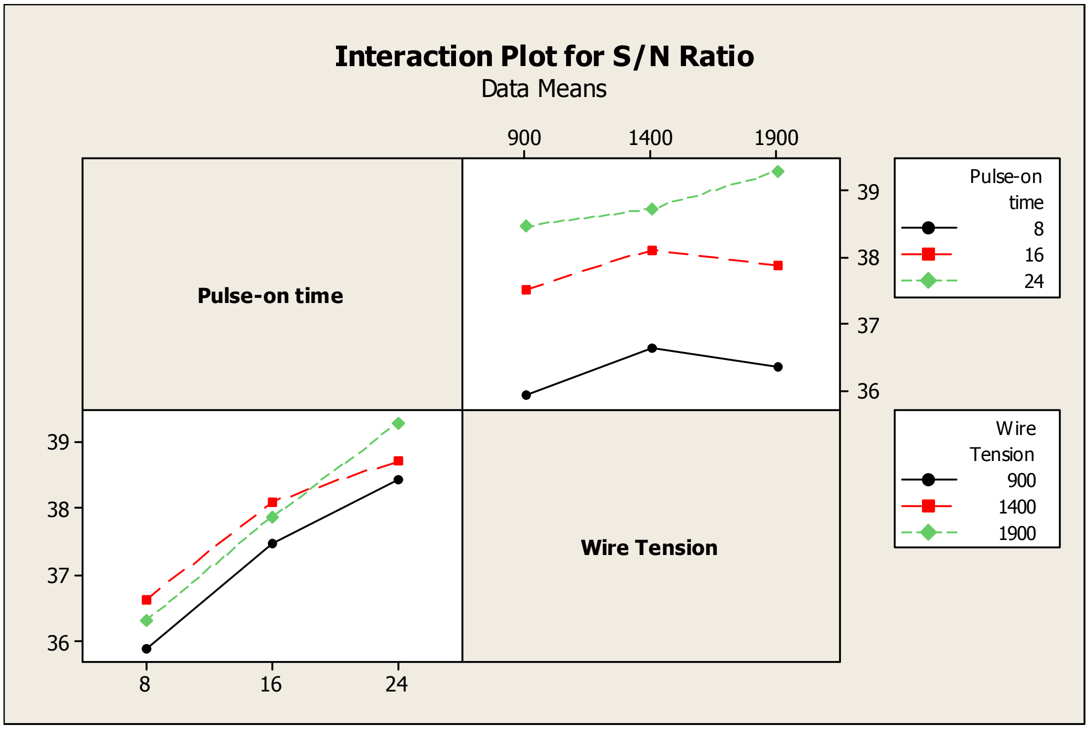


Figure 5.3: Effects of Process Parameters Interaction on Cutting rate of zinc coated wire (S/N ratio)

Interaction graph has been plot between Pulse-on time and Wire Tension to show the effect at different levels. The results from ANOVA tables comply with the results from the interaction figures (5.3).

5.2.1.2 Brass Wire on AISI H-13 Die steel

Now, Brass wire-electrode is being used with AISI H-13 die steel workpiece to study the effect of cutting rate on machining with Wire-cut EDM.

Table 5.4: Experimental results of cutting rate for brass wire electrode

Exp. No.	Cutting Rate (mm/hr)		S/N Ratio
	R1	R2	
1	43.596	43.284	32.7576
2	47.766	46.188	33.4340
3	45.378	43.920	32.9928
4	52.350	52.908	34.4241
5	52.074	52.944	34.4038
6	49.884	50.358	34.0001
7	62.786	61.344	35.8552
8	55.704	56.106	34.9488
9	56.388	57.456	35.1045

Minitab software again has been used to calculate Signal to Noise Ratios to analyze the experimental result. Minitab software assigns ranks based on delta values based on S/N ratio which is difference is the highest average minus the lowest average for each factor in descending order; the highest delta value has ranked 1 and ranked 2 is assigned to the second highest, and so on to other parameters. The ranks indicate the relative importance of each factor to the response.

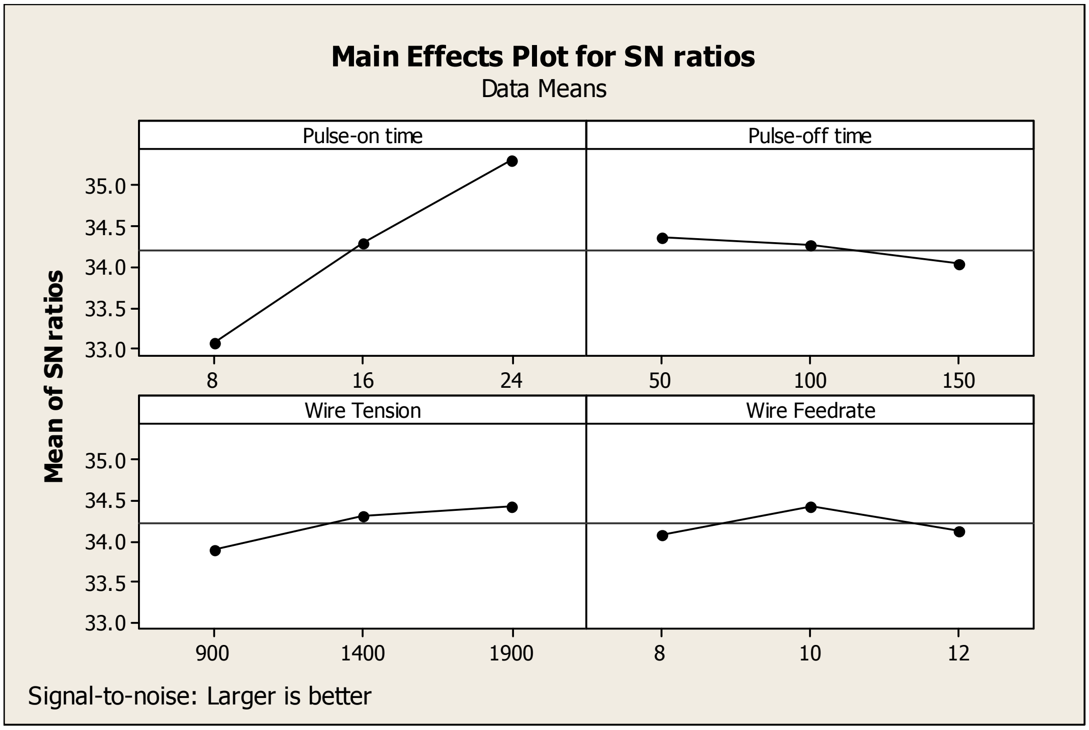


Figure 5.4: Effect of process parameter on cutting rate with Brass wire electrode (S/N ratio)

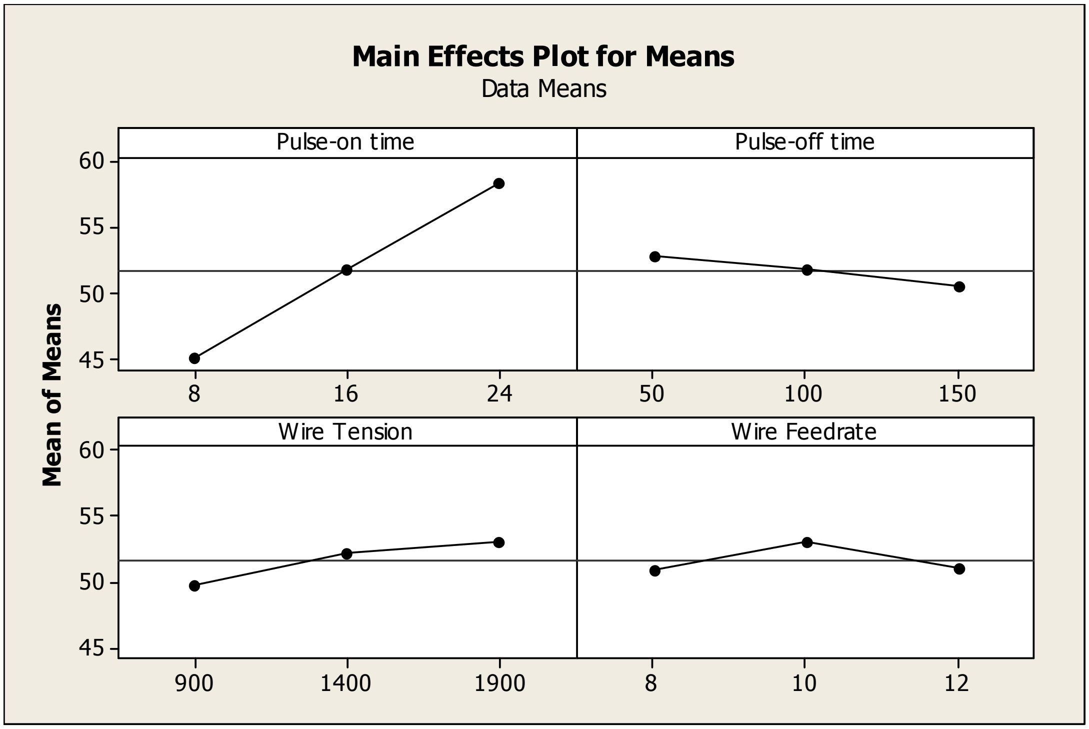


Figure 5.5: Effect of process parameter on cutting rate with Brass wire electrode (Raw Data)

Again, Cutting rate should be large as much as possible. So, for that Minitab software is being set for "Larger the Better" mode to find out the levels at which maximum cutting rate is being achieved.

Figure (5.4) & (5.5) shows that the third level of Pulse-on time (Ton_3), the first level of Pulse-off time ($Toff_1$), third level Wire tension (T_3) and Second level of Wire Feedrate (W_2) provide the maximum value of cutting rate with brass electrode. The same levels of the parameters (Ton_3, $Toff_1$, T_3 and W_2) are the best levels for the maximum cutting rate with brass wire electrode in Wire-cut EDM process are achieved by raw data analysis.

Table 5.5: Response Table for S/N Ratios of cutting rate with brass wire

Level	Pulse-on Time	Pulse-off Time	Wire Tension	Wire Feedrate
1	33.06	34.35	33.90	34.09
2	34.28	34.26	34.32	34.43
3	35.30	34.03	34.42	34.12
Delta	2.24	0.31	0.52	0.34
Rank	1	4	2	3

S/N ratio provided by rank table shows that Pulse-on time has maximum contribution followed by wire tension, wire feedrate and pulse-off time respectively for maximum cutting rate as they ranked 1, 2, 3 and 4 respectively.

Table 5.6: Analysis of Variance for S/N ratio of cutting rate with brass wire

Parameters	**Degrees of Freedom**	**Sum of Squares**	**Mean Square**	**F-factor**	**Factor Effect (percent contribution)**	**Optimum Level**
Pulse-on Time	2	7.5531	3.7766	45.1035	90.2070	Ton_3
Pulse-off Time	2	0.1579	0.0789	0.9426	1.8853	-
Wire Tension	2	0.4499	0.2249	2.6863	5.3726	T_3
Wire Feedrate	2	0.2123	0.1061	1.2675	2.5351	-
Total	8	8.3731	4.1865		100.0000	

In order to find the significance of the process parameters towards cutting rate ANOVA table was established. Form the table of ANOVA (analysis of variance) for the S/N ratio it was concluded that both Pulse-on time and Wire tension significantly affects the variation in the cutting rate values. It is also evident that Pulse-off time and Wire feedrate are non-significant process parameters for cutting rate. Optimum levels for Pulse-on time and Wire Tension are (Ton_3) and (T_3) respectively.

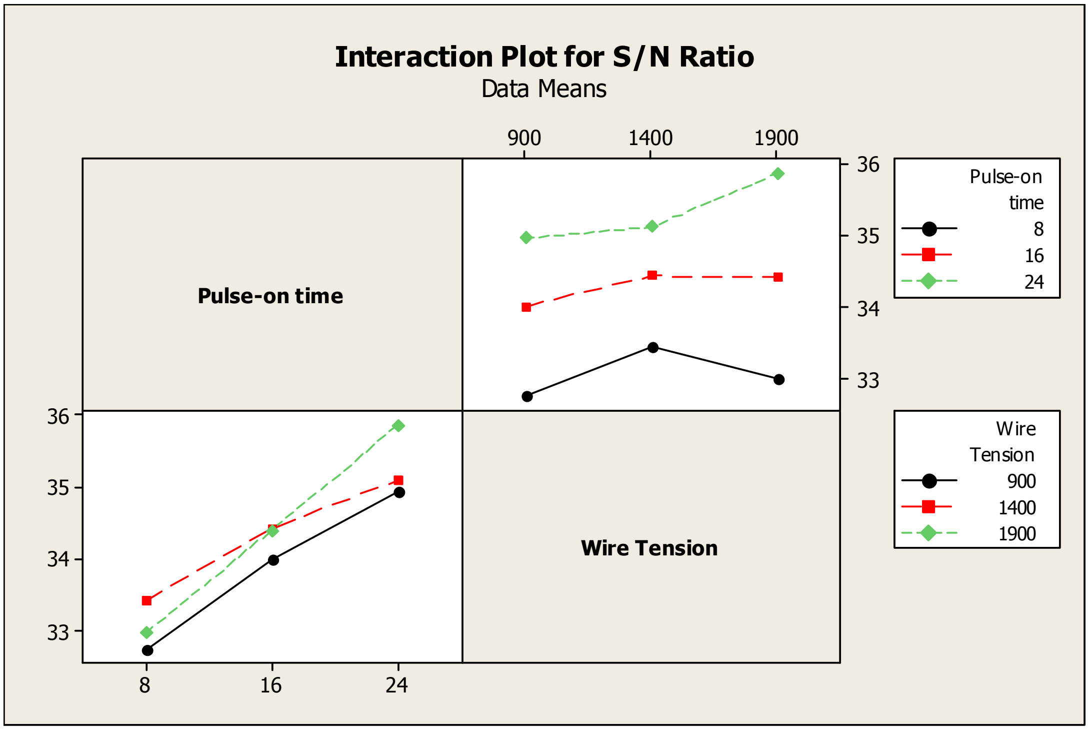


Figure 5.6: Effects of Process Parameters Interaction on Cutting rate of Brass wire (S/N ratio)

Interaction graph has been plot between Pulse-on time and Wire Tension to show the effect at different levels. The results from ANOVA tables comply with the results from the interaction figures (5.6).

5.2.2 Effect on Surface roughness

Experiments based on the L9 OA were performed in order to see the influence of process parameters on surface roughness. The surface roughness was measured with Taylor-Hobson Surtronic3+ surface roughness tester instrument. The surface roughness of raw data and their

S/N ratio data for each work piece is given in the tables for each trial. The figures in each section for work pieces and wires are plotted based on the raw data and S/N data.

5.2.2.1 Zinc Coated Wire on AISI H-13 Die steel

Zinc coated wire-electrode has been used on AISI H-13 die steel workpiece with two no. of trials with same process parameters under same conditions to avoid any bias in investigation.

Table 5.7: Experimental results of surface roughness for Zinc coated wire electrode

Exp. No.	**Surface Roughness (μm)**		**S/N Ratio**
	R1	**R2**	
1	2.32	2.35	-7.36592
2	2.51	2.49	-7.95887
3	2.59	2.61	-8.29953
4	3.10	3.05	-9.75719
5	2.88	2.90	-9.21801
6	2.74	2.72	-8.72331
7	3.25	3.22	-10.1976
8	3.12	3.09	-9.84133
9	3.19	3.21	-10.1030

Surface roughness should be small as much as possible. So, for that Minitab software is being set for “Smaller the Better” mode to find out the levels at which minimum surface finish is being achieved.

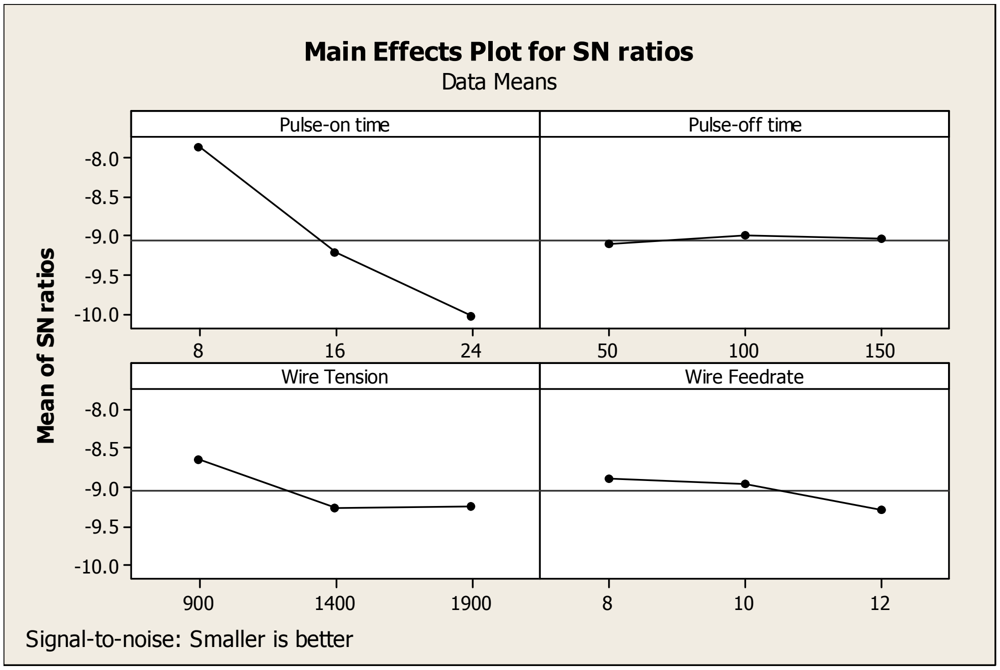


Figure 5.7: Effect of process parameter on surface roughness with zinc coated wire (S/N ratio)

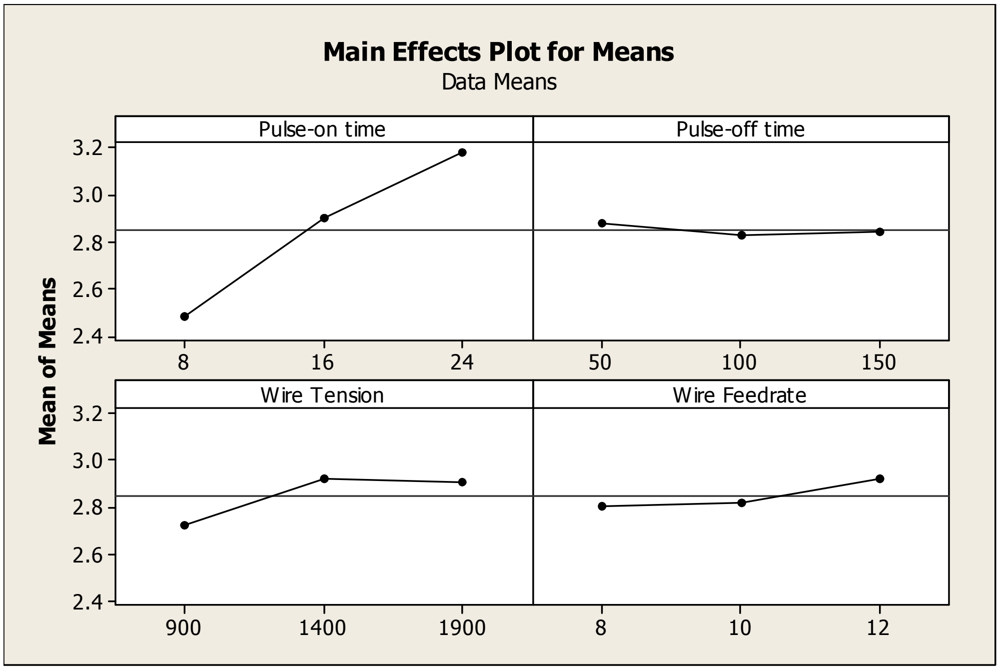


Figure 5.8: Effect of process parameter on surface roughness with zinc coated wire (Raw Data)

Figure (5.7) & (5.8) shows that the first level of Pulse-on time (Ton_1), the second level of Pulse-off time ($Toff_2$), first level Wire tension (T_1) and first level of Wire Feedrate (W_1) provide the minimum value of surface roughness with zinc coated wire electrode. The same levels of the parameters (Ton_1, $Toff_2$, T_1 and W_1) are the best levels for the minimum surface roughness with zinc coated wire electrode in Wire-cut EDM process are achieved by raw data analysis.

The following table shows which significant control factor has the most impact on surface roughness.

Table 5.8: Response Table for S/N Ratios of surface roughness with zinc coated wire

Level	Pulse-on Time	Pulse-off Time	Wire Tension	Wire Feedrate
1	-7.875	-9.107	-8.644	-8.896
2	-9.233	-9.006	-9.273	-8.960
3	-10.047	-9.042	-9.238	-9.299
Delta	2.173	0.101	0.630	0.404
Rank	1	4	2	3

S/N ratio provided by rank table shows that Pulse-on time has maximum contribution followed by wire tension, wire feedrate and pulse-off time respectively for minimum surface finish as they ranked 1, 2, 3 and 4 respectively.

Table 5.9: Analysis of Variance for S/N ratio of surface roughness with zinc coated wire

Parameters	**Degrees of Freedom**	**Sum of Squares**	**Mean Square**	**F-factor**	**Factor Effect (percent contribution)**	**Optimum Level**
Pulse-on Time	2	7.2277	3.6138	43.6612	87.3224	Ton_1
Pulse-off Time	2	0.0157	0.0078	0.0947	0.1893	-
Wire Tension	2	0.7513	0.3757	4.5387	9.0774	T_1
Wire Feedrate	2	0.2823	0.1412	1.7054	3.4108	-
Total	8	8.2770	4.1385	50.0000	100.0000	

In order to find the significance of the process parameters towards cutting rate ANOVA table was established. Form the table of ANOVA (analysis of variance) for the S/N ratio it was concluded that both Pulse-on time and Wire tension significantly affects the variation in the surface roughness values. It is also evident that Pulse-off time and Wire feedrate are non-significant process parameters for surface roughness. Optimum levels for Pulse-on time and Wire Tension are (Ton_1) and (T_1) respectively.

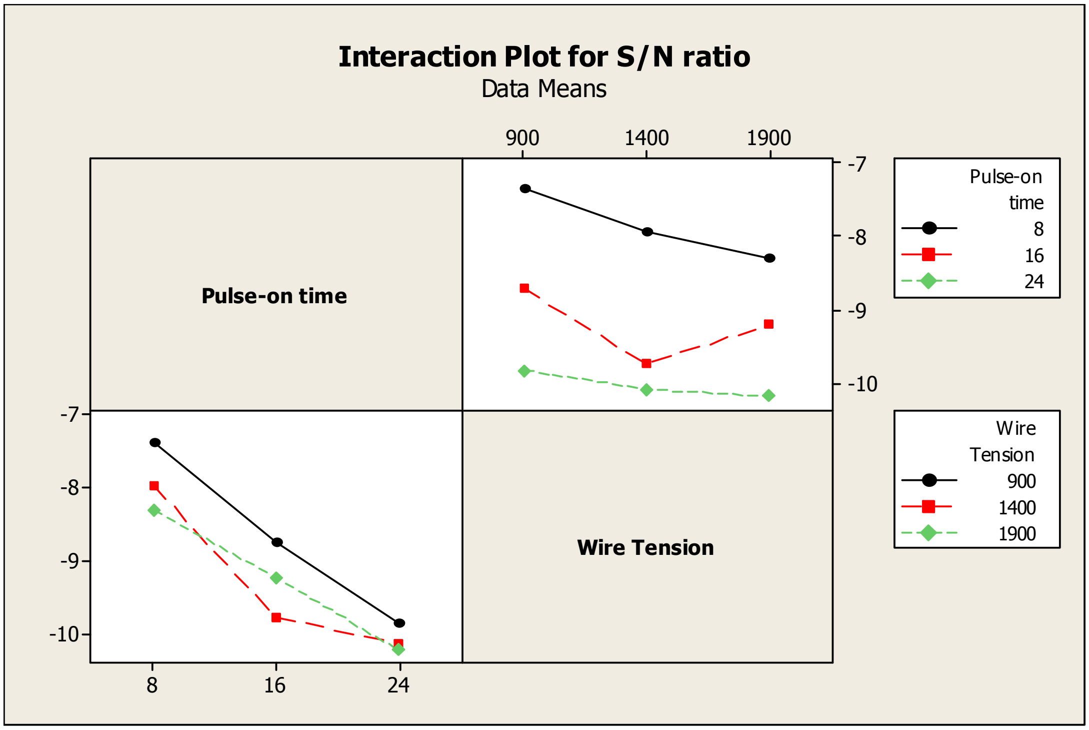


Figure 5.9: Effects of Process Parameters Interaction on surface roughness of zinc coated wire (S/N ratio)

Interaction graph has been plot between Pulse-on time and Wire Tension to show the effect at different levels. The results from ANOVA tables comply with the results from the interaction figures (5.9).

5.2.2.2 Brass Wire Electrode on AISI H-13 Die steel

Brass wire-electrode has been used on AISI H-13 die steel workpiece with two no. of trials with same process parameters under same conditions to avoid any bias in investigation.

Table 5.10: Experimental results of surface roughness for brass wire electrode

Exp. No.	Surface Roughness (µm)		S/N Ratio
	R1	R2	
1	2.54	2.58	-8.16506
2	2.71	2.69	-8.62733
3	2.79	2.83	-8.97435
4	3.19	3.21	-10.1030
5	3.10	3.12	-9.85525
6	2.91	3.07	-9.51653
7	3.59	3.54	-11.0414
8	3.32	3.35	-10.4620
9	3.41	3.43	-10.6806

Surface roughness should be small as much as possible. So, for that Minitab software is being set for “Smaller the Better” mode to find out the levels at which minimum surface finish is being achieved. Ra (µm) value has been used to predict the surface roughness of the workpiece material in each case of trial with different wire electrodes.

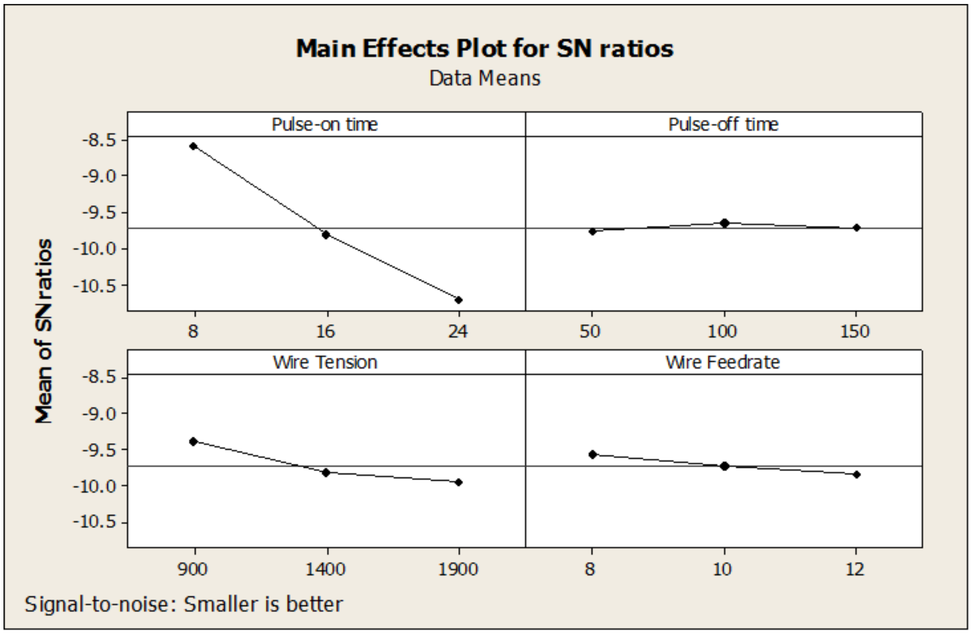


Figure 5.10: Effect of process parameter on surface roughness with brass wire (S/N ratio)

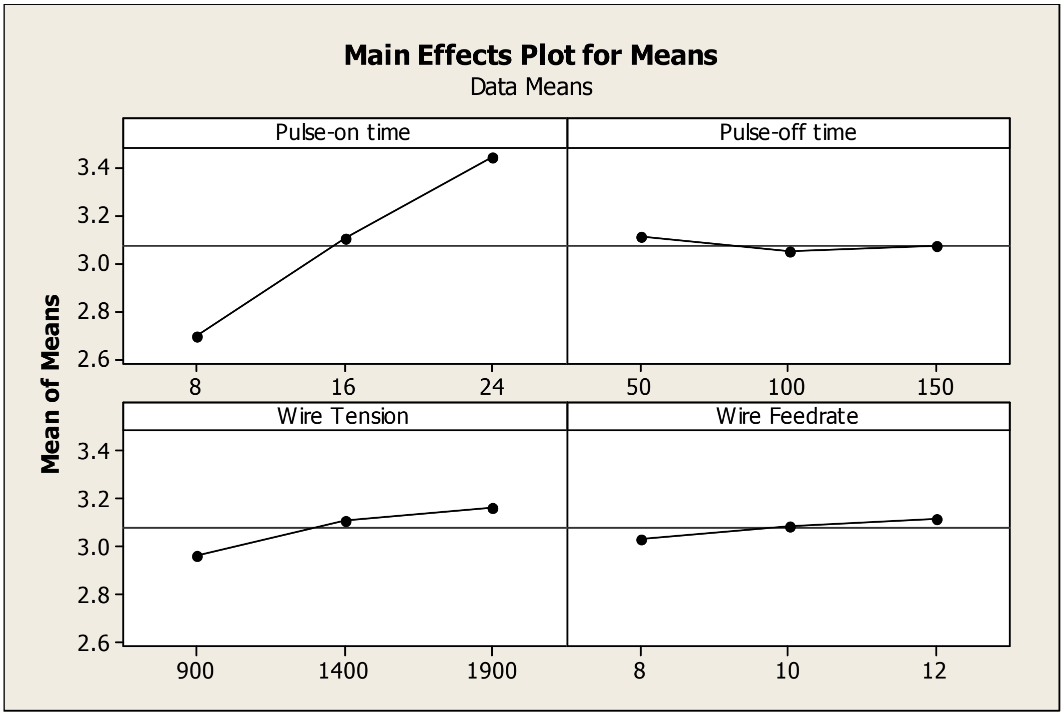


Figure 5.11: Effect of process parameter on surface roughness with brass wire (Raw Data)

Figure (5.10) & (5.11) shows that the third level of Pulse-on time (Ton_1), the first level of Pulse-off time ($Toff_2$), third level Wire tension (T_1) and Second level of Wire Feedrate (W_1) provide the minimum value of surface roughness with zinc coated wire electrode. The same levels of the parameters (Ton_1, $Toff_2$, T_1 and W_1) are the best levels for the minimum surface roughness with zinc coated wire electrode in Wire-cut EDM process are achieved by raw data analysis.

The following table shows which significant control factor has the most impact on surface roughness.

Table 5.11: Response Table for S/N Ratios of surface roughness for brass wire electrode

Level	Pulse-on Time	Pulse-off Time	Wire Tension	Wire Feedrate
1	-8.589	-9.770	-9.381	-9.567
2	-9.825	-9.648	-9.804	-9.728
3	-10.728	-9.724	-9.957	-9.846
Delta	2.139	0.122	0.576	0.280
Rank	1	4	2	3

S/N ratio provided by rank table shows that Pulse-on time has maximum contribution followed by wire tension, wire feedrate and pulse-off time respectively for minimum surface finish as they ranked 1, 2, 3 and 4 respectively.

Table 5.12: Analysis of Variance for S/N ratio of surface roughness for brass wire electrode

Parameters	**Degrees of Freedom**	**Sum of Squares**	**Mean Square**	**F-factor**	**Factor Effect (percent contribution)**	**Optimum Level**
Pulse-on Time	2	6.9189	3.4594	45.5599	91.1199	Ton_1
Pulse-off Time	2	0.0226	0.0113	0.1490	0.2981	-
Wire Tension	2	0.5335	0.2668	3.5132	7.0264	T_1
Wire Feedrate	2	0.1181	0.0591	0.7779	1.5557	-
Total	8	7.5932	3.7966	50.0000	100.0000	

ANOVA table has been used to the find significance of the process parameters towards surface roughness. Form the table of ANOVA (analysis of variance) for the S/N ratio it was concluded that both Pulse-on time and Wire tension significantly affects the variation in the surface roughness values.

It is also evident that Pulse-off time and Wire feedrate are non-significant process parameters for surface roughness. Optimum levels for Pulse-on time and Wire Tension are (Ton_1) and (T_1) respectively.

Interaction graph has been plot between Pulse-on time and Wire Tension to show the effect at different levels. The results from ANOVA tables comply with the results from the interaction figures (5.12).

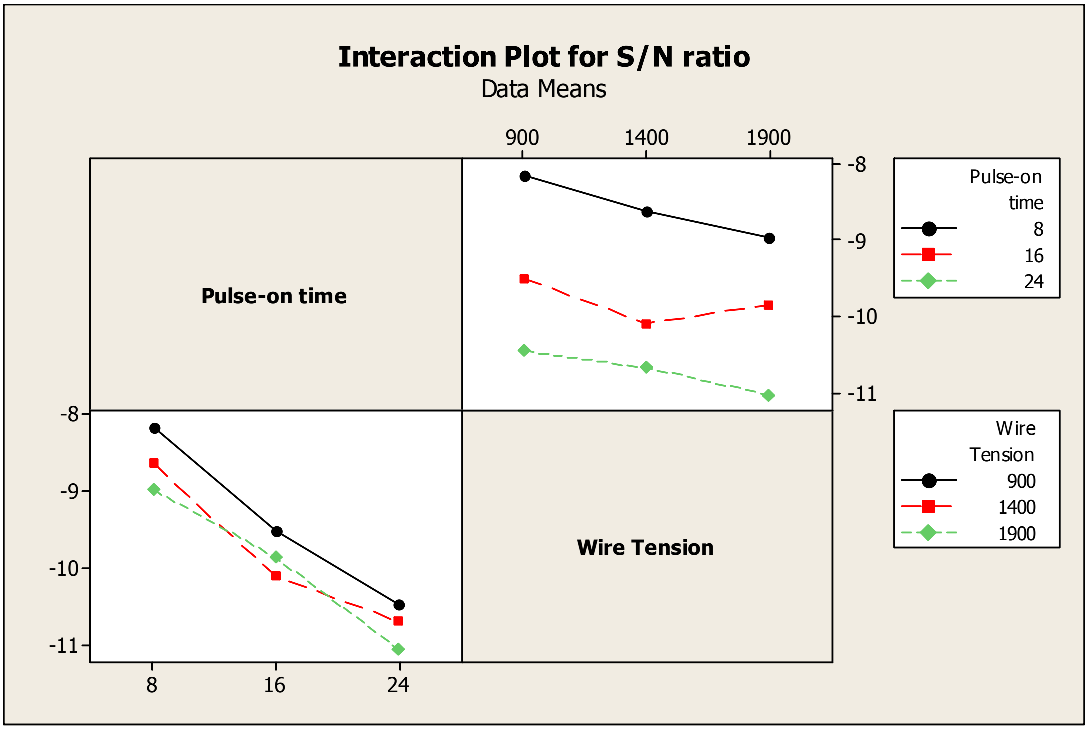


Figure 5.12: Effects of Process Parameters Interaction on surface roughness of brass wire (S/N ratio)

5.2.3 Effect on Metal Removal Rate

Experiments based on the L9 OA were performed in order to see the influence of process parameters on metal removal rate. Metal removal rate describes the volumetric machining efficiency of the system.

Metal removal rate of raw data and their S/N ratio data for each work piece is given in the tables for each trial. The figures in each section for work pieces and wires are plotted based on the raw data and S/N data.

Metal removal rate is calculated :-

$$MRR = V_c . b. h \ (mm^3/min) \qquad [34]$$

Where, V_c = cutting rate, mm/min;

b =width of cut, mm;

h= height of the work piece, mm.

Where, width of cut (b) for each workpiece is different for each trial of brass wire and zinc coated wire experiments. The value of width of cut of each trail for brass wire electrodes is

Shown in Table no. (5.13) and for zinc coated wire electrode is shown in Table no. (5.14).

Table 5.13: Width of cut for brass wire of each trial

	Brass wire			
	Trial 1		Trial 2	
Exp. No.	Total cut	cut width	Total cut	cut width
1	12.684	0.684	12.694	0.694
2	12.764	0.764	12.768	0.768
3	12.779	0.779	12.831	0.831
4	12.604	0.604	12.584	0.584
5	12.753	0.753	12.724	0.724
6	12.819	0.819	12.811	0.811
7	12.731	0.731	12.776	0.776
8	12.768	0.768	12.795	0.795
9	12.728	0.728	12.749	0.749

Table 5.14: Width of cut for Zinc coated wire of each trial

	Zinc coated wire			
	Trial 1		Trial 2	
Exp. No.	Total cut	cut width	Total cut	cut width
1	12.701	0.701	12.760	0.760
2	12.811	0.811	12.730	0.730
3	12.720	0.720	12.780	0.780
4	12.602	0.602	12.680	0.680
5	12.698	0.698	12.740	0.740
6	12.699	0.699	12.751	0.751
7	12.680	0.680	12.740	0.740
8	12.660	0.660	12.770	0.770
9	12.640	0.640	12.718	0.718

5.2.3.1 Zinc Coated Wire on AISI H-13 Die steel

Zinc coated wire-electrode has been used on AISI H-13 die steel workpiece with two no. of trials with same process parameters under same conditions to avoid any bias in investigation.

Table 5.15: Experimental results of metal removal rate for Zinc coated wire electrode.

Exp. No.	Metal Removal Rate (mm^3/min)		S/N Ratio
	R1	R2	
1	22.6459	24.4977	27.4277
2	25.0295	28.2303	28.4603
3	25.9976	26.9719	28.4555
4	27.1141	25.1353	28.3223
5	28.0667	29.5454	29.1811
6	28.0510	30.0022	29.2412
7	32.1763	33.0078	30.2601
8	28.1019	33.1411	29.6322
9	28.3990	32.5188	29.6146

Metal removal rate should be large as much as possible. So, for that Minitab software is being set for “Larger the Better” mode to find out the levels at which maximum metal removal rate is being achieved.

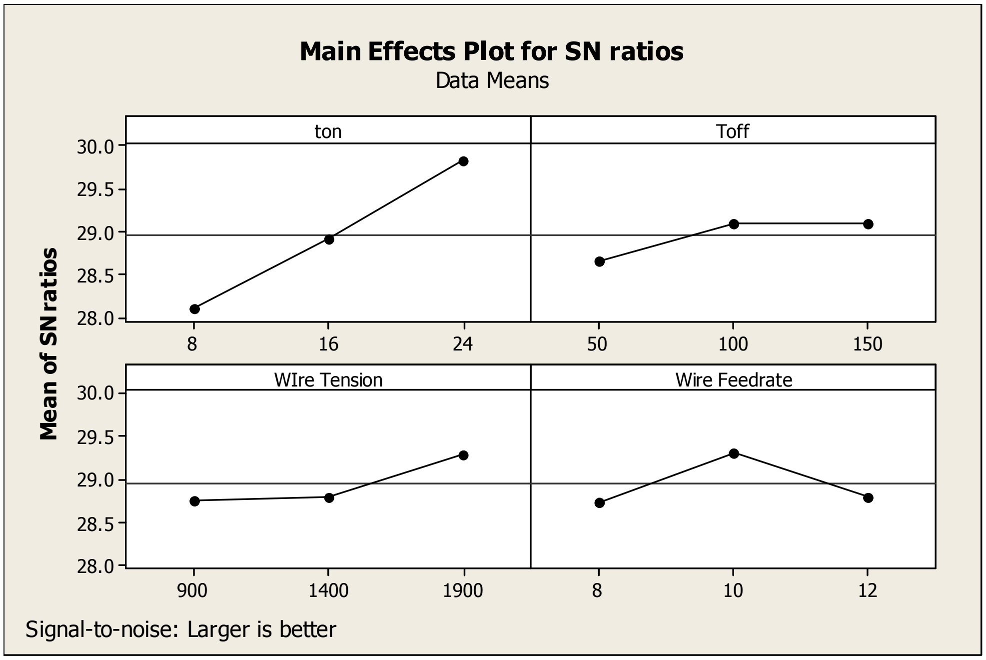


Figure 5.13: Effect of process parameter on metal removal rate with zinc coated wire (S/N ratio)

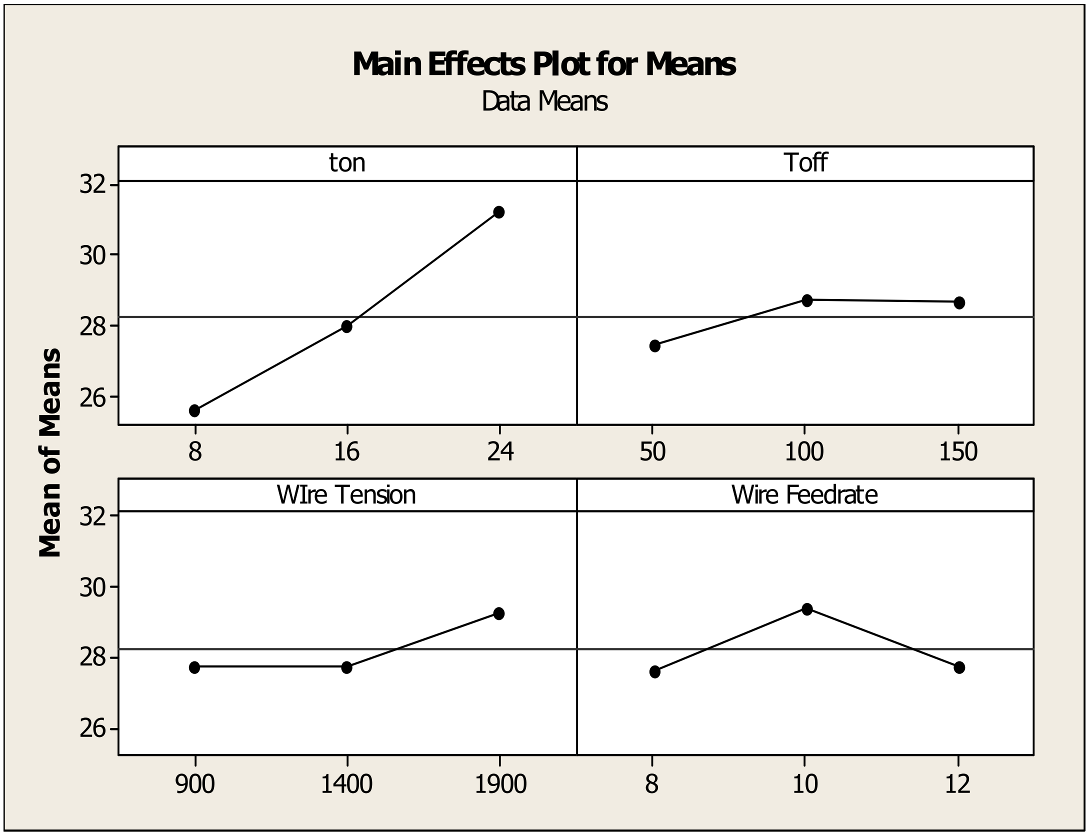


Figure 5.14: Effect of process parameter on metal removal rate with zinc coated wire (Raw Data)

Figure (5.13) & (5.14) shows that the third level of Pulse-on time (Ton_3), the third level of Pulse-off time ($Toff_3$), third level Wire tension (T_3) and Second level of Wire Feedrate (W_2) provide the maximum value of metal removal rate with zinc coated wire electrode.

The same levels of the parameters (Ton_3, $Toff_3$, T_3 and W_2) are the best levels for the maximum metal removal rate with zinc coated wire electrode in Wire-cut EDM process are achieved by raw data analysis.

The following table shows which significant control factor has the most impact on metal removal rate.

Table 5.16: Response Table for S/N Ratios of metal removal rate with zinc coated wire

Level	Pulse-on Time	Pulse-off Time	Wire Tension	Wire Feedrate
1	28.11	28.67	28.77	28.74
2	28.91	29.09	28.80	29.32
3	29.84	29.10	29.30	28.80
Delta	1.72	0.43	0.53	0.58
Rank	1	4	3	2

S/N ratio provided by rank table shows that Pulse-on time has maximum contribution followed by wire feedrate, wire tension and pulse-off time respectively for maximum metal removal rate as they ranked 1, 2, 3 and 4 respectively

Table 5.17: Analysis of Variance for S/N ratio of metal removal rate with zinc coated wire

Parameters	**Degrees of Freedom**	**Sum of Squares**	**Mean Square**	**F-factor**	**Factor Effect (percent contribution)**	**Optimum Level**
Pulse-on Time	2	4.4507	2.2254	37.3566	74.7132	Ton_3
Pulse-off Time	2	0.3656	0.1828	3.0689	6.1378	$Toff_3$
Wire Tension	2	0.5337	0.2668	4.4795	8.9590	T_3
Wire Feedrate	2	0.6070	0.3035	5.0950	10.1900	W_2
Total	8	5.9571	2.9785	50.0000	100.0000	

In order to find the significance of the process parameters towards metal removal rate ANOVA table was established. Form the table of ANOVA (analysis of variance) for the S/N ratio it was concluded that Pulse-on time, Pulse-off time, Wire tension and Wire feedrate significantly affects the variation in the surface roughness values. It is evident that all are significant process parameters for metal removal rate. Optimum levels are Pulse-on time (Ton_3), Pulse-off time ($Toff_3$), Wire Tension (T_3) and Wire Feedrate (W_2).

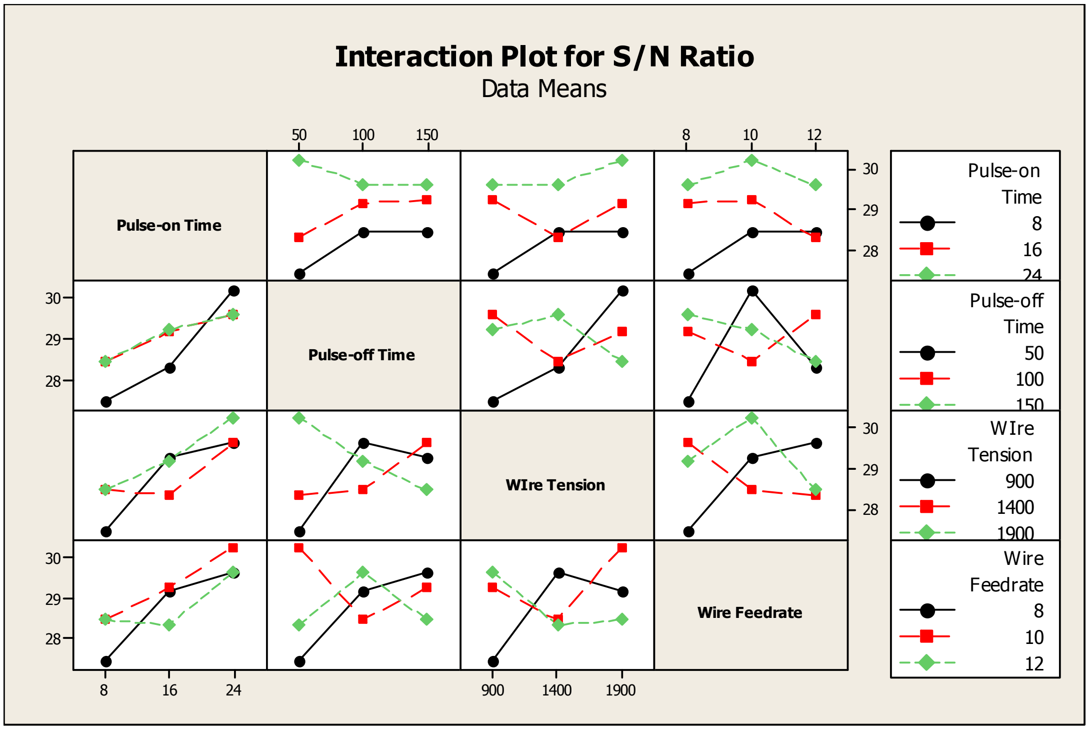


Figure 5.15: Effects of Process Parameters Interaction on Metal Removal Rate of zinc coated wire (S/N ratio)

Interaction graph has been plot between all process parameter which are Pulse-on time, Pulse-off time, Wire tension, Wire feedrate to show the effect at different levels. The results from ANOVA tables comply with the results from the interaction figures (5.15).

5.2.3.2 Brass Wire on AISI H-13 Die steel

Brass wire-electrode has been used on AISI H-13 die steel workpiece with two no. of trials with same process parameters under same conditions to avoid any bias in investigation.

Metal removal rate should be large as much as possible. So, for that Minitab software is being set for “Larger the Better” mode to find out the levels at which maximum metal removal rate is being achieved.

Table 5.18: Experimental results of metal removal rate for brass wire electrode

Exp. No.	Metal Removal Rate (mm^3/min)		S/N Ratio
	R1	R2	
1	15.4068	13.5133	23.1475
2	18.8548	18.3035	25.3777
3	18.2639	18.8571	25.3685
4	16.3367	15.9641	24.1619
5	20.2594	19.8046	26.0328
6	21.1084	21.1008	26.4876
7	23.7055	24.6109	27.6567
8	22.1033	23.0455	27.0667
9	21.2094	22.2345	26.7307

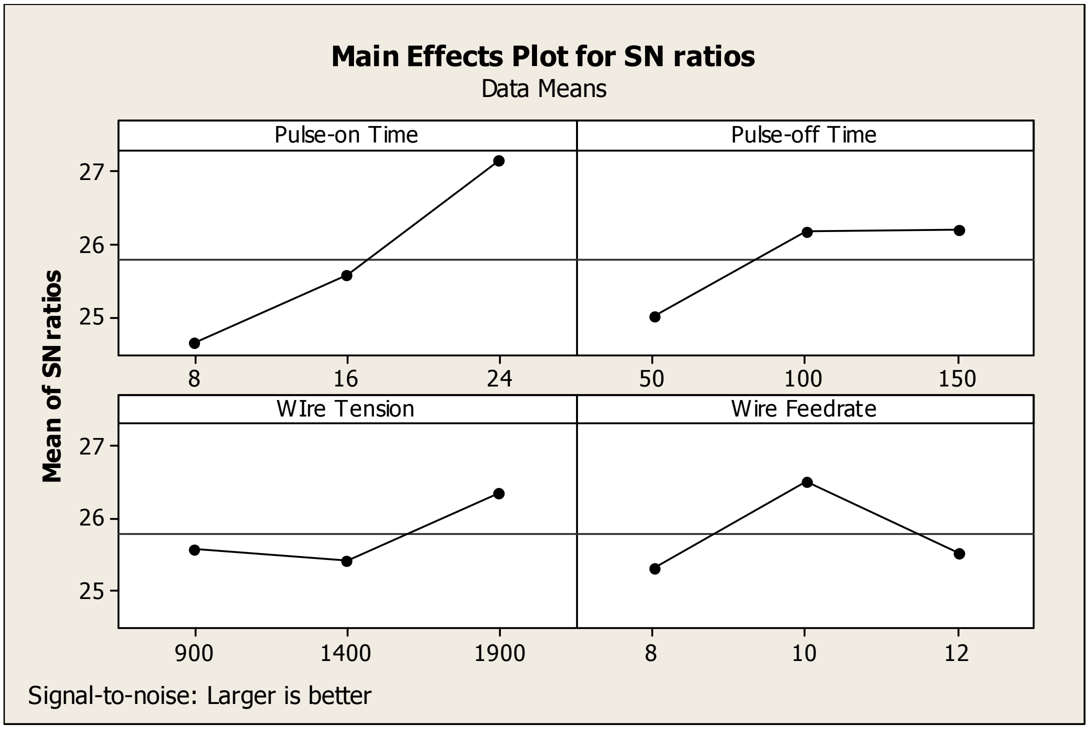


Figure 5.16: Effect of process parameter on metal removal rate with brass wire (S/N ratio)

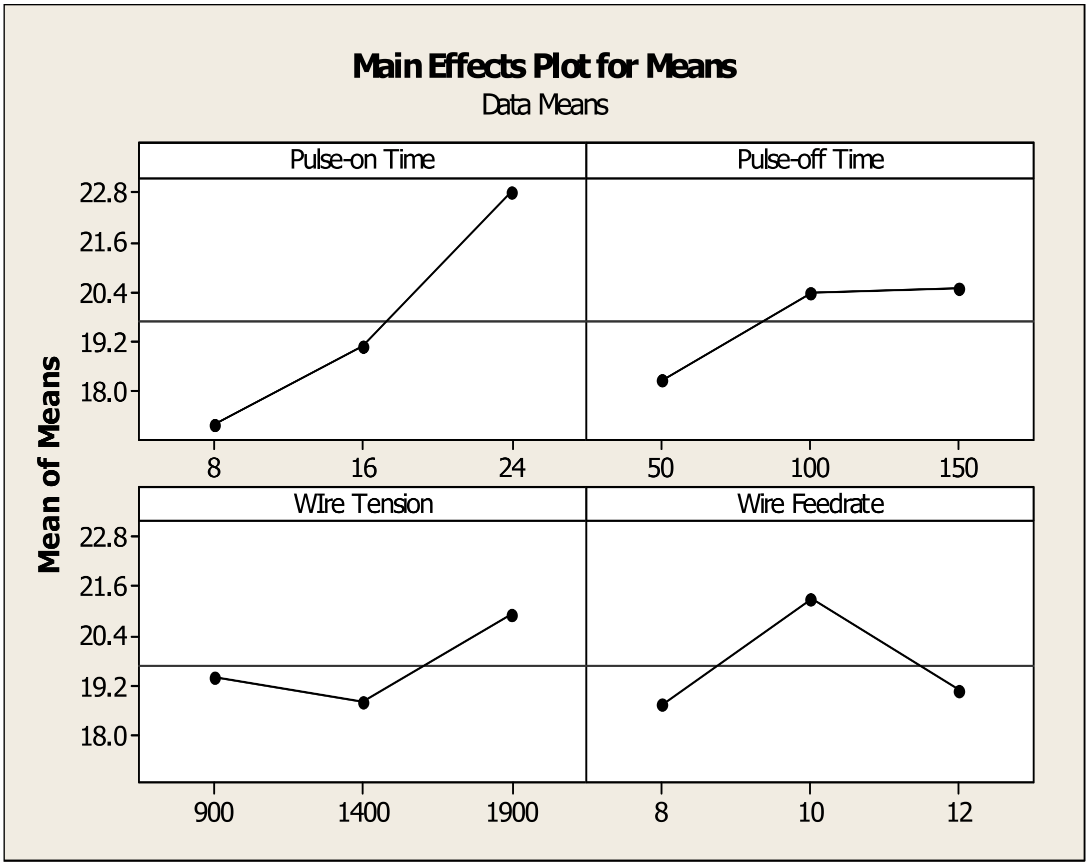


Figure 5.17: Effect of process parameter on metal removal rate with brass wire (Raw Data)

Figure (5.16) & (5.17) shows that the third level of Pulse-on time (Ton_3), the third level of Pulse-off time ($Toff_3$), third level Wire tension (T_3) and Second level of Wire Feedrate (W_2) provide the maximum value of metal removal rate with zinc coated wire electrode.

The same levels of the parameters (Ton_3, $Toff_3$, T_3 and W_2) are the best levels for the maximum metal removal rate with zinc coated wire electrode in Wire-cut EDM process are achieved by raw data analysis.

The following table shows which significant control factor has the most impact on metal removal rate.

Table 5.19: Response Table for S/N Ratios of metal removal rate for brass wire electrode

Level	Pulse-on Time	Pulse-off Time	Wire Tension	Wire Feedrate
1	24.63	25.21	25.57	25.3
2	25.56	26.16	25.22	26.51
3	27.15	26.20	26.35	25.53
Delta	2.52	0.99	1.13	1.21
Rank	1	4	3	2

S/N ratio provided by rank table shows that Pulse-on time has maximum contribution followed by wire feedrate, wire tension and pulse-off time respectively for maximum material removal rate as they ranked 1, 2, 3 and 4 respectively.

Table 5.20: Analysis of Variance for S/N ratio of metal removal rate for brass wire electrode

Parameters	**Degrees of Freedom**	**Sum of Squares**	**Mean Square**	**F-factor**	**Factor Effect (percent contribution)**	**Optimum Level**
Pulse-on Time	2	8.3525	4.1763	30.9016	61.8032	Ton_3
Pulse-off Time	2	1.9115	0.9557	7.0718	14.1436	$Toff_3$
Wire Tension	2	1.3122	0.6561	4.8549	9.7097	T_3
Wire Feedrate	2	1.9385	0.9692	7.1718	14.3435	W_2
Total	8	13.5147	6.7574		100.0000	

In order to find the significance of the process parameters towards metal removal rate ANOVA table was established. Form the table of ANOVA (analysis of variance) for the S/N ratio it was concluded that Pulse-on time, Pulse-off time, Wire tension and Wire feedrate significantly affects the variation in the surface roughness values.

It is evident that all are significant process parameters for metal removal rate. Optimum levels are Pulse-on time (Ton_3), Pulse-off time ($Toff_3$), Wire Tension (T_3) and Wire Feedrate (W_2).

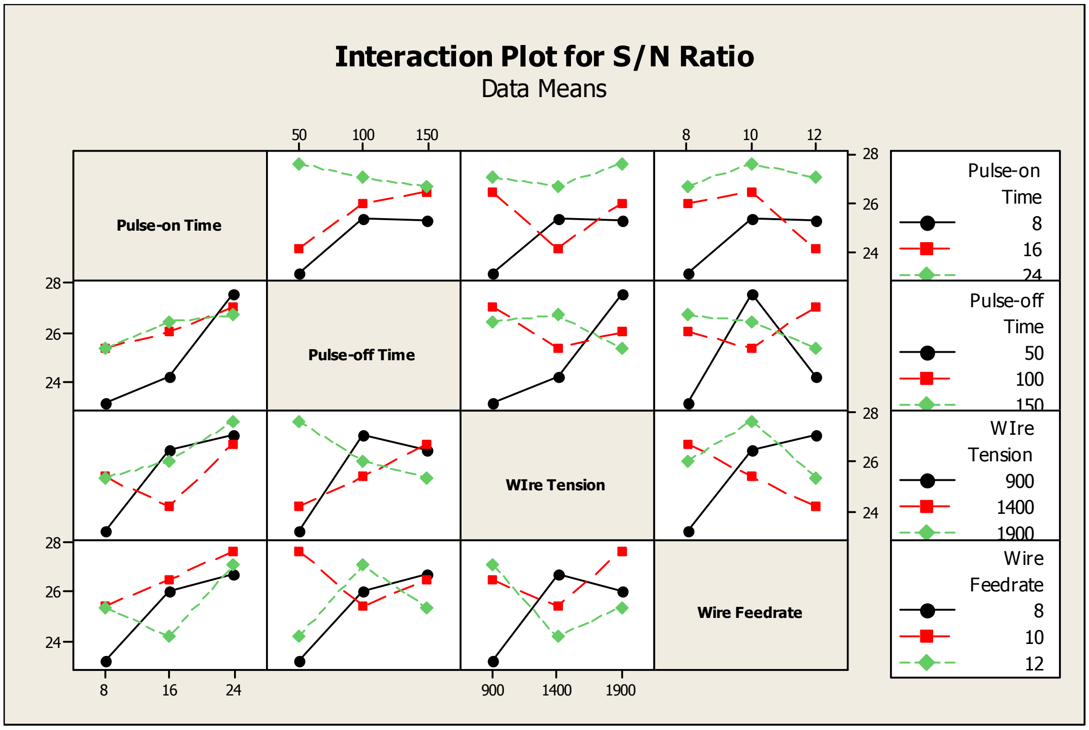


Figure 5.18: Effects of Process Parameters Interaction on Metal Removal Rate of brass wire electrode (S/N ratio)

Interaction graph has been plot between all process parameter which are Pulse-on time, Pulse-off time, Wire tension, Wire feedrate to show the effect at different levels. The results from ANOVA tables comply with the results from the interaction figures (5.18).

Chapter 6

Wire Properties and Influences on Wire-Cut EDM Performance

6.1 Introduction

Wire-cut electrical discharge machining (Wire-cut EDM) is a non-traditional machine whose technique is able to produce more complicated and 3-D shapes through difficult to machine metals with better accuracy and desirable surface finish without using high cost grinding or expensive formed tools. Wire-cut electrical discharge machine should satisfy performance demands of products such as: high-speed cutting, resistant against wire breakage and accurate machining to improve the productivity and to achieve high quality machining work pieces.

Many factors have effect on the process of Wire-cut EDM (cutting rate and work piece precision) including electrical parameters of machine tool and wire electrode. Higher taper angle, thicker workpiece, automatic wire threading, and long periods of unattended operation, make choosing the optimum wire a much more critical factor in achieving a successful operation.

Wire-cut EDM system core is wire electrode which is used to receive a stable electrical discharge spark. So, the wire electrode is one of the important factors contributing the overall Wire-cut EDM performance. Wire electrode rupture is one of the serious problems associated to Wire-cut EDM process and wire electrode. This problem affects surface finish quality and accuracy, limits the cutting rate and increases machining period. Wire-cut EDM and work pieces requirements vary greatly, which can make selection of the correct wire is an acute task. As a result, experimentation with different wire electrode types is necessary if optimum results are to be achieved [39]

Wire breakage poses a constant threat to Wire-cut EDM productivity, but Wire-cut EDM operators can avoid wire breakage and keep their operations running smoothly and efficiently with some knowledge about the wire-cut EDM process, causes for wire rupture and the behaviour of wire and work pieces materials when they are subject to the process.

6.2 Wire Breakage 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 its characteristics, a cross-section reduction and the increase in wire electrode temperature.

A high temperature, varying work piece thickness and process parameters influence the wire strength that affects the wire rupture. Researchers provided an experiment to study wire breakages during machining. They figured out the relationship between stresses developed and tensile strength in frequency of wire rupture. They concluded that wire's thermal and mechanical properties have main effect on wire rupture [40].

The section explains some crucial reasons of wire rupture in details. Also, analysis and experiments are presented to show the effect of machining parameters 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 workpiece increases. Several researches were explored in this subject. They established their own results in machine parameters adjustment and work piece thickness. A multi-input model established to show the stochastic relationship between average gap feedback voltages, discharging frequency and work table feed rate.

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.

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. Several researchers studied the thermal energy distribution along the wire electrode and proposed different thermal model with different method.

A thermal model for Wire-cut EDM was developed to describe the temperature distribution along a thin wire in theory. Also, performed several experiments to establish the effect of thermal load on wire breakages. A mathematical thermal model was proposed in order to examine the relative influence of various process parameters on the thermal load of the wire. 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 [41].

Researchers showed the wire rupture decrease when wire feed rate 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-cut EDM Performance

There are numbers of parameters that influence the Wire-cut EDM performance. New dielectrics, work piece and wire materials are considered as constant factors in order to research the performance of Wire-cut EDM. Among the mentioned factors contribute to improve the Wire-cut EDM performance, advancement of new materials for wire used in Wire-cut EDM 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 electrode is only about 10% of the Wire-cut EDM process cost. A high performance of Wire-cut EDM is measured by low wire breakage, high-speed cutting and high precision machining of workpiece [42].

The wire electrode used in Wire-cut EDM 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 of wire electrode helps the energy transfers to work piece efficiently and also, minimize energy loss of sparking during machining. The wire electrodes with high tensile strength are a good heat resistance in high temperature and remain straight under vibration and tension. The low melting temperature of wire electrode improves the spark formation and decrease dielectric fluid ionization time. Higher thermal conductivity of the wire electrode ensures a better spark discharge energy distribution during the machining process. This will increase the material removal rate (MRR).

Figure 6.1: Requirements of wire electrode material

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 rate is achieved by high energy [43].

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

6.3.1 Types of Wire Electrode

Wire utilizes a thin wire as an electrode for the erosion process. Since the level of electrical current is required for the process is great, failure to use the correct electrode materials will result in the wire eroding from the current and not the workpiece material as planned [44].

The primary concerns when choosing the wire electrode should be:-

- Adequate tensile strength with high fracture toughness.
- High electrical conductivity
- Good flush ability
- Low melting point
- Low energy requirement to melt and vaporize

The two types of wire electrode that can be used in the wire-cut EDM Industries:-

- Single component wire
- Multi-Component composite wire

6.3.1.1 Single component wire:-

- These types of wire were the conventional type, which used the copper and molybdenum as its material of component.
- Other type of material that being used in the single component wire are :-

a. **Cooper wire**

This wire being used because:-

1. Being used at the place when at the beginning of the wire-cut EDM and also known as “The engineer wire”.
2. It has a high electrical conductivity.
3. Can be found in a small diameter wire.
4. Low tensile strength.

b. Molybdenum wire

The molybdenum wire is a popular type wire once and the characteristics are such as:

1. Tensile strength of 280,000 psi.
2. Melting temperature of 4757 F and a poor flush ability.
3. Can be found in 0.2mm to 0.4mm diameter
4. The cost of using the material is quite expensive.
5. Being replaced to hard aluminium-brass wire in its application.

c. Brass wire

These wires have been used as a good compromised between the copper and the molybdenum because:

1. High machining speed from 1.1 mm^2/ hour in 2mm workpiece thickness.
2. Today the wire can cut at $28mm^2$ to 30 mm^2 per hour.
3. Can be found in different tensile strength to suit the machining application. For the plain brass, the tensile strength is from 70,000 psi to 130,000 psi.
4. This has proven that the wire is better than the usage of Copper and molybdenum.

6.3.1.2 Multi-Component composite wire

- Single component wire still limited by a compromise among properties. So multi component composites were being used to address each requirement independently.
- The coating component is applied to improve flushing task during the machining. The effectiveness of the coated is limited by the coating thickness which relatively thin about 5-10 microns to 1 millionth of a meter.
- Below are the types of material being used in the Multi-component composite wire

.

a. Zinc coated copper wire

1. High Conductivity copper core with an additional of 0.4% of Magnesium.
2. It is rough with micro cracks on the surface layer to improve the flushing operation.

3. Can cut high material such as graphite and aluminium alloys with superior accuracy
4. The wire is high resistance to breakage and suitable for production runs.

b. Zinc coated brass wire

1. It has as good mechanical straightness and high tensile strength of 35,000psi and very accurate in cutting.
2. The properties make it suitable for the use of general purpose where a greater speed and excellent finish are required.
3. Because of its high tensile strength , it is suitable to cut a smaller diameter involving 0.003mm,0.004mm and 0.006mm diameter.

c. Silver coated brass wire

1. Develop in 1990 to offer a traditional wire user and offer much cheap cost rather than the usage of zinc coated wire.
2. The material of these wire were more to brass than the coated wire where silver coated wire will increase the machining speed at an economical price.
3. The key of the wire's performing is the efficient transfer of electrical energy from the carbide power contact to the wire itself.

The various coatings are applied to the electrode are consumed during the cutting process, enabling the corresponding effect. The coating is only effective to the depth in which it is applied, about 5-10 microns (or 1 millionth of a meter), this limitation is less apparent in thinner workpiece. As technologies improve, thicker layer of coatings are developed, and more research is performed that determine which compounds produce the best results based on the application, the use of multi-composite, stratified wire is sure to become the dominant choice for most applications.

6.4 Experimental Procedure

Experiments were done to find the wire characteristics for two wire types, Brass wire electrode and Zinc Coated wire, in association with work pieces types of AISI H-13 die steel.

The objective was to compare the influence of uncoated wires and coated wire on Wire-cut EDM performance. Therefore, the cutting rate, surface roughness and metal removal rate are measured on work piece materials as a scale of comparison. AISI H-13 hot chromium die steel is regarded as "difficult-to-machine" materials due to their susceptibility to work hardening during machining. 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 Breakage

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-on time (Ton) and Pulse-off time (Toff) are the most crucial machining parameters that are effective in wire breakage. The wire ruptures probability increases when pulse-on time increases and pulse-off time decreases simultaneously. The number of discharges within a given period of time becomes more when pulse-off time (Toff) is shorter and the pulse-on time (Ton) is higher leads to higher electrical discharging energy which will generate more heat energy. Therefore, due to the excessive thermal load on workpiece and an increased discharge leads to wire breakages.

On the other hand, wire tension (T) is effective parameters in reduction of wire breakage when pulse-on time and pulse-off time are small and big enough respectively. Wire tension reduction can decrease wire rupture possibility while machining. Wire breakage during AISI H-13 die steel machining is sensitive to changing of electrical parameters such as time between Pulse-on time, pulse-off time, wire tension and wire feed-rate when machining with brass wire.

Zinc coated wire resistance against wire rupture in tough conditions, high pulse duration and low pulse frequency, is much more than brass wire for work piece materials. Because, coated layer should decrease the risk of rupturing wires because it protects the core of the wire electrode from thermal shock of electrical discharge sparks and increases the wire mechanical tensile strength. In fact, the tensile strength of zinc coated wire is more than normal brass wire. The tensile strength (142,000 + PSI) of zinc coated wire is more than the brass wire tensile strength (130,000 + PSI).

6.4.2 Cutting Rate

The range of cutting rate with zinc coated wire electrode is higher than brass wire electrode. The higher cutting rate is more desirable during Wire-cut EDM machining.

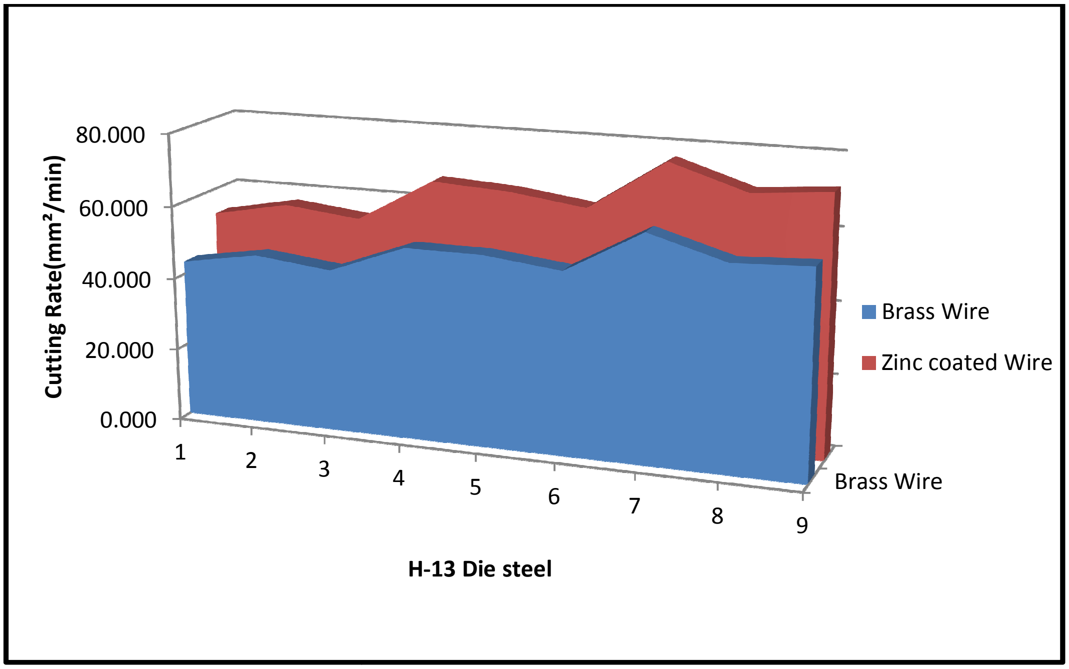


Figure 6.2: Cutting Rate with different wires

The cutting rate of AISI H-13 die steel zinc coated wire electrode under the same operational parameters is 30% higher than brass wire electrode as shown in Figure (6.2). Good sparing properties of zinc layer on brass core result in improved cutting rate. In fact, the addition of zinc to brass wire leads to reduction in the wire melting point. The high melting temperature of wire improves the spark formation and leads to less dielectric ionization time. Thus, the cutting rate improves with zinc coated wire.

6.4.3 Surface Roughness

The surface roughness values for AISI H-13 die steel machined with zinc-coated wire electrode is less than AISI H-13 die steel machined with brass wire electrode. The lesser surface roughness is desirable.

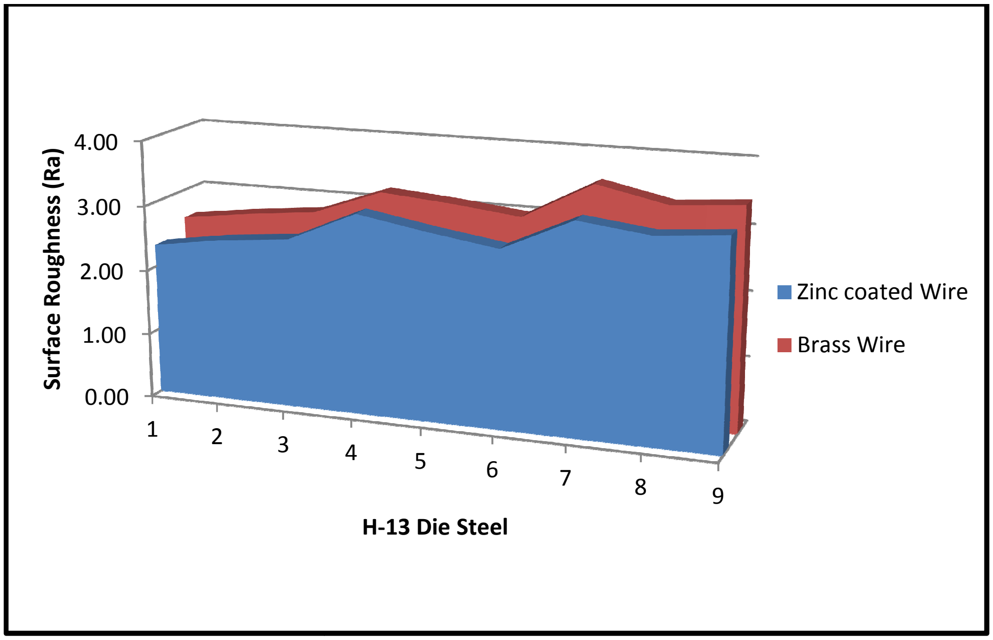


Figure 6.3: Surface Roughness with different wires

Zinc-coated wire electrode leads to smoother surface in comparison with brass wire electrode as shown in Figure (6.3). The existence of zinc in coated brass wire provides a higher tensile strength for wire electrode.

The wire electrode having high tensile strength is a good heat resistance in high temperature and maintains straightness under vibration and mechanical tension in wire electrode. As well as, the uniform layer of zinc on core provides good discharge characteristics. Good discharge characteristics and higher tensile strength can be achieved through finer discharge which can be created with zinc coated wire.

It leads to low surface roughness in case of zinc coated wire electrode machining surface as compare to brass wire electrode, overall zinc coated wire electrode provides improved quality of machining surface.

6.4.4 Metal removal rate

The range of metal removal rate with zinc coated wire electrode is higher than brass wire electrode. The higher metal removal rate is more desirable during Wire-cut EDM machining.

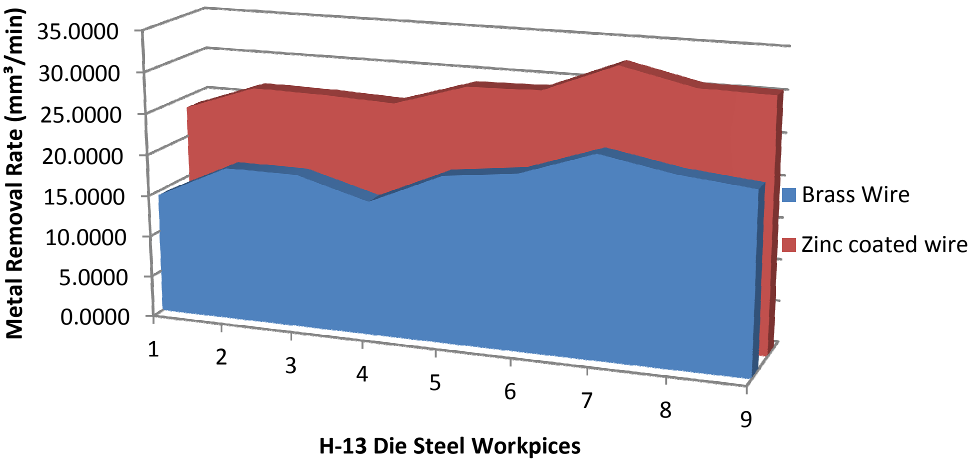


Figure 6.4: Metal Removal Rate with different wires'

Zinc coated wire electrode provides better metal removal rate than brass wire electrode because coating provides more strength to the wire which leads more spark generation with greater moving speed as shown in figure (6.4).There is significant 30% increment as been seen in metal removal rate with zinc coated wire as compare to brass wire electrode.

Chapter 7

Conclusion and Recommendations

7.1 Conclusion

In this investigation, the influence of zinc-coated brass wire electrode on the performance of Wire-cut EDM (wire breakage, cutting rate, surface roughness and metal removal rate) was compared with brass in order to develop an approach to perform a high performance and cost efficient Wire-cut EDM machining of AISI H-13 die steel. As well as, various machining situations were studied to determine the effect of process parameters on the responses variables (breakage, cutting rate, surface roughness and metal removal rate).

Based on the experiments and analysis, the following conclusions can be drawn:

- The pulse-on time and wire tension have significant effect on cutting rate in machining of AISI H-13 Die Steel with both types of wire electrode. As the Pulse-on time and wire tension increases cutting rate also increases.

- The pulse-on time and wire tension have significant effect on cutting rate in machining of AISI H-13 Die Steel with both types of wire electrode. As the Pulse-on time and wire tension decreases surface roughness also decrease.

- Zinc-coated brass wire electrode provides in higher cutting rate and smoother surface finish as compared with high-speed brass wire.

- The wire breakage probability increases when pulse-on time increases and pulse-off time decreases simultaneously. Also, Wire tension reduction can decrease wire rupture possibility.

- Wire breakage is more in brass wire electrode as compare to zinc coated wire electrode at high tension which makes a significant impact on machining time which leads to low productivity of system.

- The pulse-on time, Pulse-off time, wire tension, Wire feedrate all have significant effect on metal removal rate in machining of AISI H-13 Die Steel with both types of wire electrode.

7.2 Recommendations

- In this investigation, the effect of some machining parameters was investigated on wire breakage, cutting rate, surface roughness and metal removal rate. The extension of the study is to see the influence of other machining parameters and machining conditions on Wire-cut EDM performance.

- The investigation shows that zinc coated brass wire electrode provides a higher cutting rate and smoother surface finish as compare to with brass wire electrode. 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 wire materials.

- Two different types of wire electrode were used in this study to see their effects on surface roughness, cutting rate and wire breakage. The effect of other wire's properties such as shape and size on machining performance is recommended.

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