

# **Experimental Investigation of the Surface Integrity of Deep Cryogenically Treated WEDM Machined Surface**

*A Dissertation submitted*

In the Partial Fulfillment of the Requirement for the Award of

Degree of

**Master of Engineering**

in

**Production Engineering**

Submitted by

**Manpreet Singh**

**Registration No: 801382017**

**Under the Supervision of**

**Dr. Vinod Kumar**

**Dr. V.P. Agrawal**



**MECHANICAL ENGINEERING DEPARTMENT  
THAPAR UNIVERSITY, PATIALA-147004, INDIA**

**July, 2015**

# CERTIFICATE

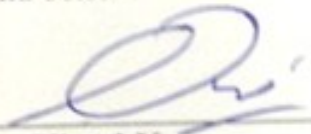
I hereby declare that the thesis entitled "Experimental Investigation of the Surface Integrity of Deep Cryogenically Treated WEDM Machined Surface" is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering in Production Engineering** at **Thapar University, Patiala** under the supervision of **Dr. Vinod Kumar**, Associate Professor, Mechanical Engineering Department, Thapar University, Patiala and **Dr. V.P. Agrawal**, Visiting Professor, Mechanical Engineering Department, Thapar University, Patiala during July, 2013 to July, 2015. No part of the matter embodied in this report has been submitted to any other University or Institute for the award of any degree.

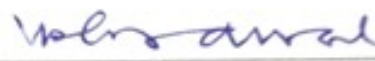
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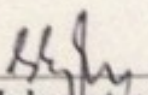
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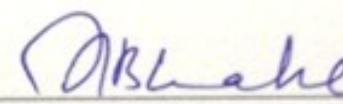
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\_\_\_\_\_  
**Dr. Vinod Kumar**  
Supervisor  
Department of Mechanical Engineering  
Thapar University, Patiala - 147004

  
\_\_\_\_\_  
**Dr. V.P. Agrawal**  
Supervisor  
Department of Mechanical Engineering  
Thapar University, Patiala - 147004

Countersigned by

  
\_\_\_\_\_  
**Dr. S.K. Mohapatra**  
Head, Mechanical Engineering Department  
Thapar University, Patiala - 147004

  
\_\_\_\_\_  
**Dr. S.S. Bhatia**  
Dean of Academic Affairs  
Thapar University, Patiala - 147004

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*Manpreet Singh*  
Manpreet Singh

# Abstract

WEDM is the most important machining method with which complex and complicated geometries can be easily machined. Based on exhaustive literature survey, it has been found that limited work has to be done on machining of deep cryogenic treated die steel AISI D3. The die steel AISI D3 plate of 150mm×150mm×10mm and deep cryogenic treated die steel plate of size 80mm×50mm×10mm is used for experimental purpose. The input process parameters pulse on time, pulse off time, spark gap set voltage and wire feed rate are investigated to check their effects on performance characteristics like material removal rate, surface roughness and percentage of dimensional deviation. The ranges of process parameters are selected based on the pilot study. In pilot study different input parameters are varied to check their effect on cutting rate. The experiments were designed using L18 orthogonal array with variation in process parameters. In this study MINITAB 16.0 software is used for designed the number of alternative experiments. The analysis of variance has to be done for study the significant factors that will greatly affect the performance characteristics. The main aim of study is to check the affect of deep cryogenic treatment on performance characteristics at same parameters conditions. Experimental results showed that material removal rate and surface roughness is increased up to 21.27% and 34% respectively and percentage of dimensional deviation is decreased up to 7.62% after deep cryogenic treatment. Scanning electron microscope (SEM) and Energy dispersive spectroscopy (EDS) of WEDM surface has been done for deep cryogenic treated and non cryogenic machined samples. The scanning electron microscope (SEM) of selected samples has been done for average recast layer thickness. It has been concluded from the results that average recast layer thickness is increased after deep cryogenic treatment because large amount of discharge energy is produced during machining in cryogenic workpiece as compared to non cryogenic workpiece. Energy dispersive spectroscopy (EDS) of WEDM samples indicates the accumulation of brass wire elements on the machined surface. Finally a hybrid of TOPSIS and AHP methods is used for parametric optimization of wire electric discharge machining. Ranking of alternative experiments of WEDM has to be done on the basis of coefficient of closeness. The coefficient of closeness found to be maximum at the experimental conditions corresponding to pulse on time: 120 unit (1.1  $\mu$ s), pulse off time: 50 unit (36  $\mu$ s), spark gap set voltage: 50 volts

and wire feed rate 5 m/min respectively, so these are the optimum parameters setting of WEDM. A MATLAB is used for evaluation of TOPSIS and AHP methods.

***Key words:*** WEDM; Cryogenic; SEM, EDS; AISI D3 die steel; TOPSIS; AHP.

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# List of Abbreviations and Symbols

WEDM	Wire Electric Discharge Machining
$T_{on}$	Pulse on time
$T_{off}$	Pulse off time
WF	Wire Feed Rate
SV	Spark Gap Set Voltage
ANOVA	Analysis of Variance
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
AHP	Analytical Hierarchy Process
MRR	Material Removal Rate
$R_a$	Arithmetic Average Surface Roughness
MADM	Multiple Attribute Decision Making
SEM	Scanning Electron Microscope
EDS	Energy Dispersive Spectroscopy
DOF	Degree of Freedom

# Chapter 1

## Introduction

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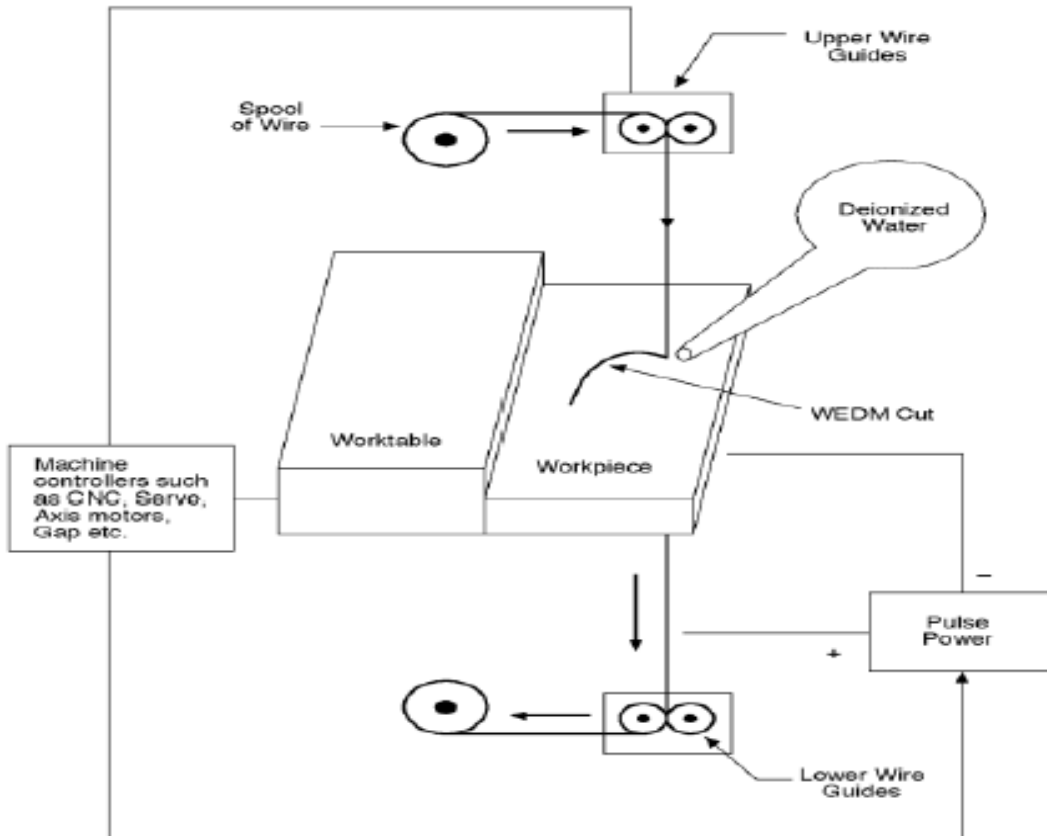
### 1.1 Wire Electric Discharge Machining (WEDM)

Wire EDM Introduced in late 1960's, and it can modernize the tool and die and metal working, aeronautics and nuclear reactors by overcome the demand of machining of high strength and temperature resistive materials (HSTR). It is a non-traditional machining process in this process tool is not directly touch with workpiece. WEDM is highly effective in accuracy, quality and productivity of industry. Every material can be machined by wire EDM but it can be conductive in nature. The materials like tool steel, hast alloy, titanium and carbides are easily machined by wire EDM process. The complex and intricate shapes can be easily produced with WEDM. The problems of machining of hardest material with conventional methods are solved with wire electric discharge machining process.

#### 1.1.1 PRINCIPLE OF WIRE EDM

Wire EDM is based on electro-thermal mechanism to machined different materials. A continuously moving wire is used as electrode, when it passes through the work piece it is taken up by second spool as shown in Figure 1.1. The applied voltage creates a large no. of electric discharges (sparks) between the electrode and work piece that is immersed in de-ionized water. Discharge is occurring due to heavy current passes through the wire and work piece with in a very small gap through de-ionized water. When electric discharge is occur the temperature can increases upto 10,000 °C to 12,000 °C the material can melt and vaporized. The removed tin bit of particles are flushed with a stream of de-ionized water.

The gap between the wire and workpiece is from 0.025mm to 0.050 mm and it is controlled by computerized controlled positioning system. Different types of wire can be used as copper, brass, zinc coated and diffused annealed. The diameter of wire ranged from 0.05mm to 0.35mm. The mechanism of material removal in WEDM is similar to EDM.

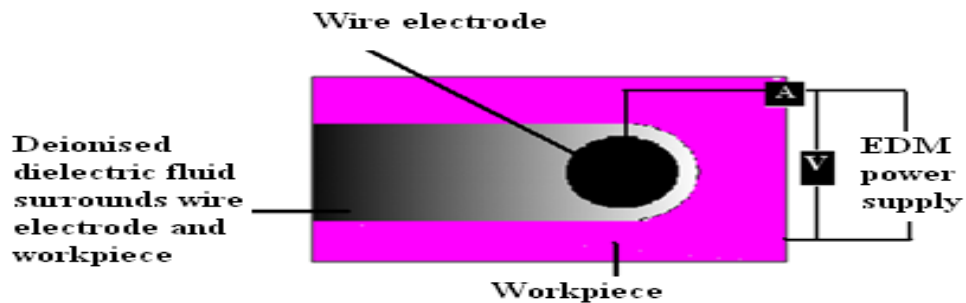


**Figure 1.1** Schematic diagram of WEDM [35]

### 1.1.2 MECHANISM OF MATERIAL REMOVAL IN WEDM

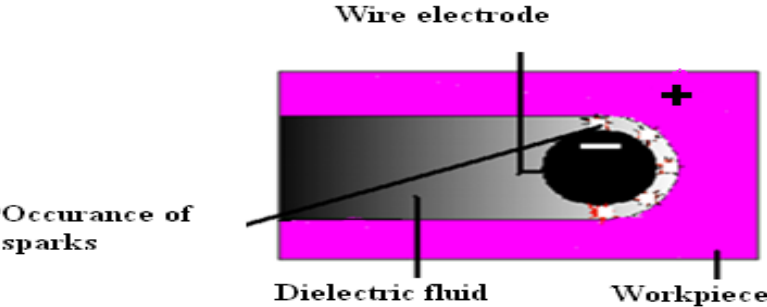
The mechanism of material removal is described in steps as:

**Step1-** The spark is generated between the wire and workpiece when power is supplied as shown in Figure 1.2. The area which is machined is surrounded by de-ionized water.



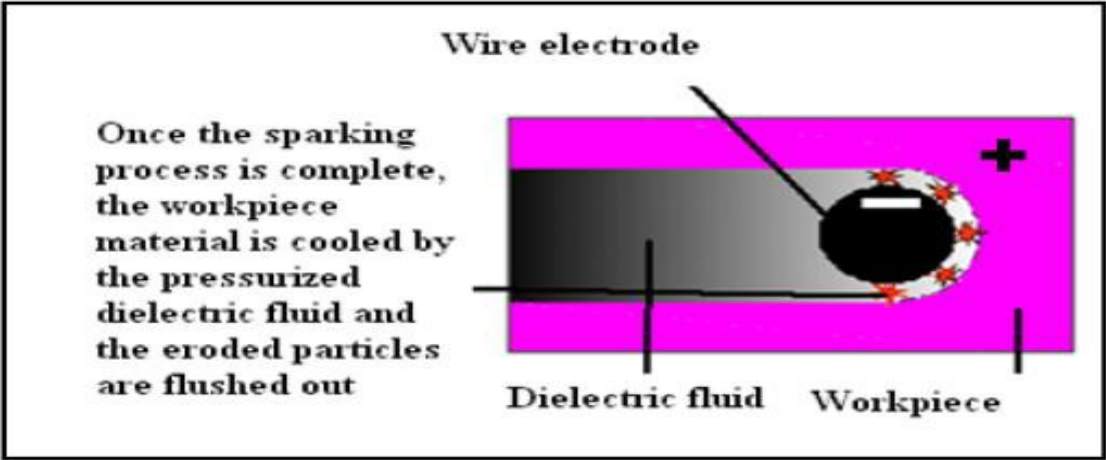
**Figure 1.2** Schematic diagram of power supply [Guitrau,1997]

**Step 2-** The spark can occur during the cycle of pulse on time as shown in Figure 1.3. The spark can occur between the wire electrode and workpiece which can erode the tin bit of particles from the surface of workpiece.



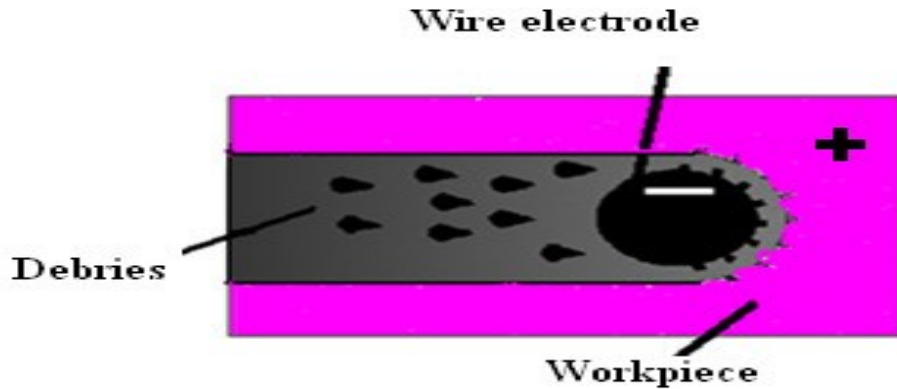
**Figure 1.3** Schematic diagram of occurrence of sparks [Guitrau,1997]

**Step 3-** The occurrence of spark process complete during the period of pulse off time. The eroded tin bit of particles cooled and flushed out by dielectric fluid as shown in Figure 1.4.



**Figure 1.4** Schematic diagram of cooling of workpiece by dielectric fluid [Guitrau,1997]

**Step 4-** When sparking process is complete the small chips and debris produced on surface of workpiece which is flushed by dielectric fluid and collected by filtration system as shown in Figure 1.5.



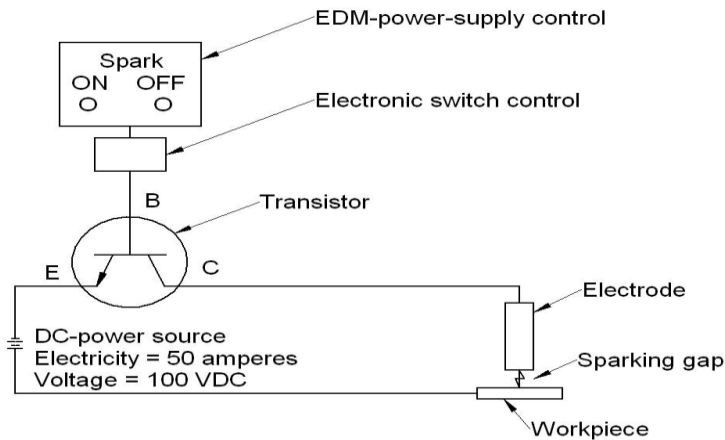
**Figure 1.5** Schematic diagram of removal of eroded tin bit of particles [Guitrau,1997]

### 1.1.3 Major Components of WEDM

A WEDM consists of major four components:

**Computerized Numerical Control-** In new advance WEDM machines the most relevant information like machine coordinates, cutting speed, NC programs and movement of wire on workpiece displayed on screen. The computerized numeric control of machine offer the different qualities for machining of intricate and complex shapes like scaling, mirror imaging, rotation and axis change. Mirror imaging is used for machining of left and right handed parts. Scaling deals with the shrink factor while machining the intricate shapes. The computerized numeric control provides the compensation for pitch error and backlash error. The machine has capability of multiple coordinates system so operator can machined different family parts from single program.

**Electric Discharge Power Unit-**The electric discharge power unit controls the pulse on time and pulse off time and it also controls the rate at which electricity is given to electrode. The basic electric circuit of electric discharge unit shown in Figure 1.6. During the cycle of pulse on time the power supply is on and then spark is produced between the workpiece and wire. When enough energy is produce then material can melt begin and vapourization ceases then the power supply is off and it is the beginning of pulse off time. The small chips and tin bit of particles can be flushed by dielectric fluid.



**Figure 1.6** Basic electrical circuit of electrical discharge unit [37]

### Mechanical Section

Table movement- The movement of table can be occurred with the help of linear motors. The computerized numeric control system controls the movement of table. For particular job work the table can be positioned with the motion controller with respect to the wire electrode. The complex and intricate shapes can be easily machined with the movement of table in different axis.

Wire path- The wire supplied from supply spool then it passes through the tension device. The wire remains straight with the help of tension device. When it is passed through the power feed contacts then electric current is supplied to wire. After machining wire passed through the lower guides then it is transmitted to waste bin.

Automatic wire threading (AWT) - The automatic wire threading offers the different capabilities to perform the multiple cut in workpice automatically with the less human intervention. When wire breakage is occur during machining then machine returns to starting point, re-thread the wire then it passes through the programmed path to the position where wire break and then continues cutting. AWT has capability to multiple cuts in the complex job and with this technique multi cut parts can cut during overnight with less human intervention.

## **Dielectric System**

Wire electric discharge machining uses de-ionized water as dielectric fluid. The dielectric system consists of water reservoir, filtration system, deionization system and water chiller unit. During machining used water drained to unfiltered side of reservoir then pass through filter and recovered in dielectric tank. The main functions of dielectric fluid are:

1. Cooling the electrode and workpiece.
2. Chips and debris produced on machined surface are flushed out by dielectric fluid.
3. Dielectric fluid cooled the vaporized material than it becomes chip upon solidification.

### **1.1.4 PROCESS PARAMETERS OF WEDM**

The WEDM consists of different process parameters like pulse on time, pulse off time, spark gap set voltage, peak current, wire tension and wire feed rate.

#### **Pulse on Time**

During the pulse on time electric discharge energy is occur because voltage is applied to gap between workpiece and electrode. When higher the pulse on time high discharge energy is produced then higher the MRR. It is measured in microseconds.

#### **Pulse off Time**

During pulse off time no voltage is applied to gap so no machining is occur during this period. In this time re-ionization of dielectric is take place and it strongly affects the cutting rate. When pulse off time is increases then less discharge energy is produced so cutting rate is decreases. Its unit is microseconds.

#### **Peak Current**

It is important parameter of WEDM. Its unit is measured in Ampere. It is the amount of power supplied to the wire EDM. When peak current is high so large amount of discharge energy is produced so MRR is increases.

### **Spark gap set voltage**

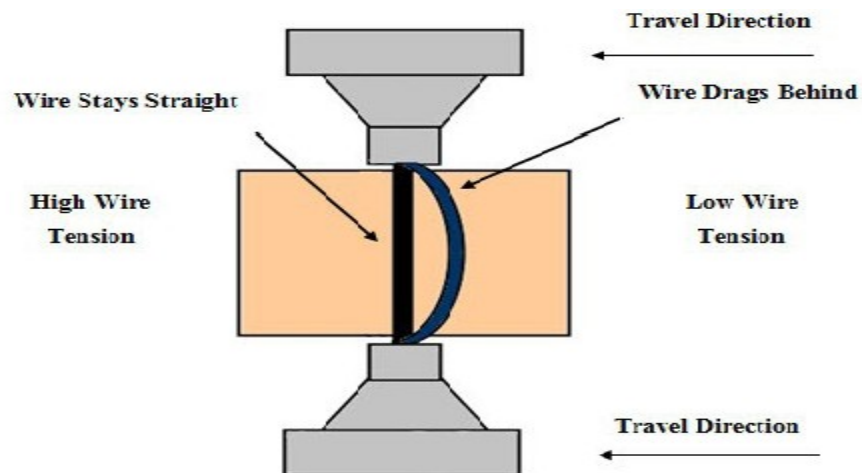
Spark gap set voltage deals with the voltage applied to gap between the wire and workpiece. When large spark gap voltage is applied then high electric discharge energy is produced in other words cutting rate is increases.

### **Servo voltage and servo feed rate**

Servo voltage deals with the advances and retracts of wire. When servo voltage is high then gap is large between the wire and workpiece so higher the servo voltage tends to lower the sparks and electrical discharge energy then cutting rate is decreases. Servo feed rate deals with the movement of table.

### **Wire Tension**

Wire tension deals with the tension of wire when the tension is high the wire becomes straight otherwise wire drag behind as shown in Figure 1.7.



### **Wire feed rate**

It deals with the feed rate of wire when higher the wire feed rate then wire consumption is increases so cost of machining is also increases.

## **1.1.5 TYPES OF WIRES USED IN WEDM AND ITS PROPERTIES**

In early 1960's when wire EDM introduced then copper wire is used because it conducts electricity. The wire diameter ranges from 0.03 mm to 0.3 mm. Now different types of wires used in WEDM are discussed in detail above.

**Copper-** In early when WEDM developed this wire is used because of its best conductivity. Now its use is limited because of its low tensile strength, high melting point and high vapour pressure.

**Brass-** This wire is an alternative to copper wire for the better performance of WEDM because it overcomes the drawbacks of copper wire. This wire is made from copper and zinc, copper ranges from 63-65 % and zinc ranges from 35-37 %. The addition of zinc provides high tensile strength, low melting point and high vapour pressure rating.

**Coated wires-** These wires consist of a core of copper or brass to enable conductivity and high tensile strength. For better spark and flush characteristics these wires are electroplated with pure or diffused zinc.

**Fine wires-** Molybdenum and tungsten wires are fine wires. These wires are not used for thick work because of its low conductivity and high melting point. These wires are used for high precision work on the WEDM.

The properties of different wires used in WEDM are discussed in detail below:

**Conductivity-** Higher the conductivity means wire can pass large amount of current then large discharge energy is produced so cutting rate increases.

**Tensile strength-** It is defined as ability of wire to withstand the wire tension and minimum rate of vibrations so wire breakage does not occur during the vertical straight cutting.

**Elongation-** It is defined as strength of wire to plastically deform before breakage of wire.

**Melting point-** deals with the electrode to be melted quickly by electric spark.

**Flushability-** It is ability of wire to better flushability so there are less chances of wire breakage.

### **1.1.6 ADVANTAGES OF WEDM**

1. WEDM can machined any material but it is conductive in nature.
2. WEDM include CNC, AWT and other features so it is high productive in nature.
3. There is no mechanical contact between wire and workpiece so stress is not produce during cutting.
4. Properties of material like hardness, microstructure and toughness are not barriers for WEDM during cutting.
5. WEDM machine can run during the overnight with less human intervention.
6. Complex and intricate shapes are easily machined by WEDM.
7. Jobs are machined with close tolerance there is no wastage of material.

### **1.1.7 DISADVANTAGES OF WEDM**

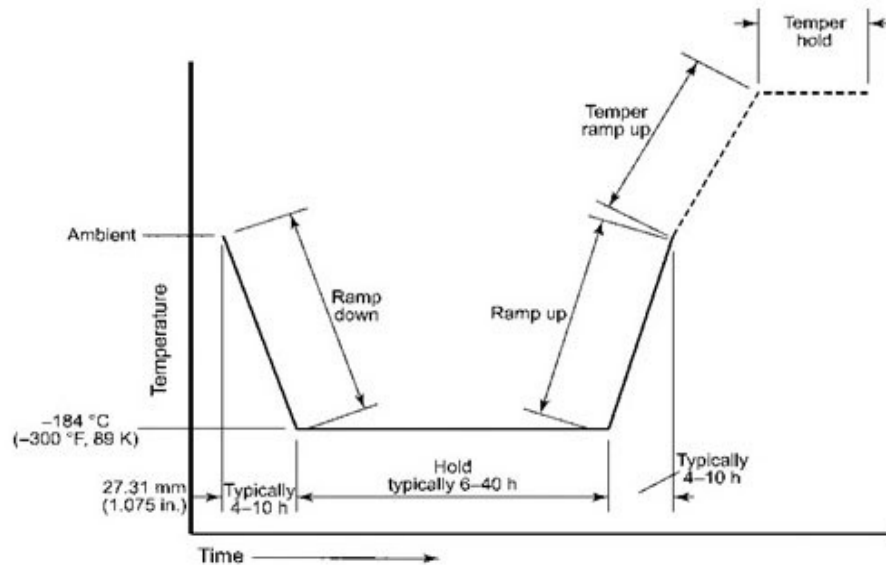
1. Higher cost is required for WEDM process.
2. WEDM is not used for very large workpiece.
3. Recast layer formation.
4. Slow cutting rate.
5. Its application limited to less thickness and conductive materials.
6. There is chances of electrolysis occur during machining.

### **1.1.8 APPLICATIONS OF WEDM PROCESS**

The application of WEDM found in several industries like mould, tool making, dies, aerospace, aircraft, jewellery and surgical equipments. The tool and dies industry products are easily produced with a single program. With CNC and AWT the processing time is reduced comparatively to other conventional manufacturing processes. WEDM also used in automobile industry for engine mountings and fuel metering valve. WEDM has great role in aerospace and aircraft industries to manufacture different components like turbine blades and rocket guidance system.

## 1.2 Deep cryogenic treatment

Deep cryogenic is defined as the cold treatment used for microstructure and mechanical change in the material. Deep cryogenic treatment is carried out in the range of  $-180^{\circ}\text{C}$  to  $-196^{\circ}\text{C}$  for a time period of 18-24 hours. The deep cryogenic treatment of workpiece carried out at Kryospace, Pune. The liquid nitrogen gas is used for complete the cryogenic treatment. The different steps for complete the cryogenic cycle are shown in figure 1.8.



**Figure 1.8** Cryogenic cycle for deep cryogenic treatment

### 1.2.1 Deep cryogenic treatment cycle

The cryogenic cycle consists of different stages ramp down, hold, ramp up and tempering are discussed in detailed below.

**Ramp down** – In this stage the temperature can be ramped down to  $-184^{\circ}\text{C}$  in a period of 4 to 10 hours as shown in figure 1.8. The slow decrease in temperature tends to minimum stresses.

**Hold**- At this stage the temperature is held at  $-184^{\circ}\text{C}$  for a period of 6 to 40 hours.

**Ramp up-** In this temperature can be taken to room temperature in a period of 4 to 10 hours as shown in figure 1.8.

**Temper ramp up-** During treatment the retained austenite is converted into martensite. For decrease the brittleness of martensite it can be brought to temper ramp up stage.

**Temper hold-** In this segment temperature can be hold at temper stage for 3 hours. Tempering temperature and hold time depends upon the size and type of part component.

### **1.2.2 Advantages of deep cryogenic treatment**

The advantages of deep cryogenic treatment are followed:

1. The conductivity of material is increased upto 5-8 % after deep cryogenic treatment.
2. The hardest materials can be machined easily after treatment.
3. Stresses can be relieved and increased wear resistance tends to reduce tool consumption.
4. The cryogenic treatment is environment friendly.

# Chapter 2

## Literature Review

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### 2.1 Literature Review Categories

Literature review can be divided into two sub categories:

1. Literature review about wire electric discharge machining.
2. Literature review about MADM-TOPSIS and AHP approach.

#### 2.1.1 Literature Review about Wire Electric Discharge Machining

[Puri and Deshpande, 2004]<sup>1</sup> applied the fuzzy logic and Taguchi techniques for optimization of wire electric discharge machining. It studies the different parameters of WEDM like gap voltage, wire feed, gap current and duty factor on machining of high carbon high chromium die steel. The output parameters are material removal rate and surface roughness. It has been found that the most important parameters that affect the performance of WEDM are gap voltage and gap current.

[Hascalyk and Caydas, 2004]<sup>2</sup> presented the experimental study of die steel D5 on wire electrical discharge machining. The input parameters are open circuit voltage, pulse duration, wire speed and dielectric fluid pressure. The responses are surface roughness and metallurgical structure. Scanning electron microscope and microhardness testing of machined samples done to check the microstructure. The wire speed and dielectric pressure does not affect the surface roughness and microstructure. The energy produced during the process is greatly affects the surface roughness and microstructure.

[Tosun et al., 2004]<sup>3</sup> analyze the various parameters of wire electric discharge machine on kerfs width and material removal rate. The analysis of variance is done to check the contributions of significant factors in performance of WEDM. Result shows that voltage and pulse duration are significant factors that will affect the output characteristics.

[Chaoi et al., 2008]<sup>4</sup> studies the effects of heat treatment on die steel STD 11 machined by WEDM. The outputs are surface roughness and microstructure of machined samples. Surface roughness is improved significantly after heat treatment due to removal of Cu particles on surface of machined samples by heat treatment. Heat affected zone of WEDM machined samples significantly by tempering. Energy dispersive X-ray spectrometer (EDS) shows that some Cu particles are stuck on the surface of machined samples due to brass wire electrode used in wire electrical discharge machining.

[Wang et al., 2008]<sup>5</sup> describe the removal of recast layer of samples machined by electric discharge machining with etching and grinding. The phosphoric acid and hydrochloric acid removes the recast layer significantly. These acids do not destroy the hardness of base material. The recast layer removal is occurring due to when corrosive acid are applied on the surface of machined samples the carbon elements are significantly reduced.

[Mohammadi et al., 2009]<sup>6</sup> studies the machining of die steel D3 by cylindrical wire electrical discharge machining and evaluate by artificial neural network and design of experiment. The inputs parameters are power, voltage, pulse off time, rotary speed and cone angle are changed and investigate the surface roughness and material removal rate. MRR is found to be depends upon workpiece geometry because it can be increase with increase in cone angle.

[Singh and Garg, 2009]<sup>7</sup> demonstrates the effects of various parameters of WEDM on machining of hot die steel H11 using one factor at a time approach. Different parameters are varied during experimentation. MRR is significantly increases with increase in pulse on time and peak current. Wire feed and wire speed are neutral parameters these parameters does not affect the material removal rate.

[Jangra et al., 2010]<sup>8</sup> optimize the wire electrical discharge machining performance characteristics by grey relational analysis. The L18 orthogonal array used to investigate the performance characteristics like cutting speed, surface roughness and dimensional deviation. The optimum value of cutting speed and dimensional deviation is found to be 3.80 mm/min and 0.008 mm respectively.

[Garg et al., 2011]<sup>9</sup> applied the response surface methodology method to investigate the parameters of wire electrical discharge machining. The desirability function is used to optimize

the different parameters with respect to performance characteristics. Cutting rate is found to be significantly increases with increase in pulse on time and peak current. The most significant factors based on ANOVA are pulse on time, pulse off time, spark gap set voltage and peak current.

[Jangra et al., 2011]<sup>10</sup> demonstrate the machining of tungsten carbide composite by WEDM. The graph theoretic approach (GTA) is used to evaluate the machinability characteristics. GTA shows that machine tool has high index value so it has great effect on machining. In this study machinability is expressed in index value. This index value is depends upon the different factors and sub factors. This methodology quantifies the different factors of WEDM and macinability index is calculated with the help of digraph and matrix representation.

[Golshan et al., 2011]<sup>11</sup> describe the machining of die steel D3 by cylindrical wire electrical discharge machining. The optimization of process is done by non dominated sorting genetic algorithm. Different input parameters are varied like current, pulse off time, voltage, rotation speed and cone angle to check the responses. The performance characteristics are material removal rate and surface roughness, a non-linear polynomial model is adopted for optimization.

[Khan and Rajput, 2012]<sup>12</sup> study the machining of high carbon high chromium steel by wire electrical discharge machining. Artificial neural network (ANN) is used to modeling and optimization of machining characteristics. Different parameters of WEDM machine are varied during experimentation to study the effect on surface roughness and cutting rate. Result shows that surface finish is less with increase in cutting rate.

[Kumar and Singh, 2012]<sup>13</sup> describes the effects of different parameters on performance of wire electric discharge machining. The L18 orthogonal array is used to perform the experiments. The output characteristics are cutting rate, surface roughness and dimensional deviation. The signal to noise ratio is calculated to optimize the experimental results. The parameters feed rate override, wire feed, servo voltage, wire tension and dielectric pressure are not significantly affect the cutting rate.

[Gill et al., 2012]<sup>14</sup> studies the machining of OHNS die steel after deep cryogenic treatment. The input Parameters are pulse on time, peak current, voltage and wire feed rate. The L27 orthogonal array used to design the experiments and to check the effect of different characteristics on

surface roughness. Scanning electron micrograph (SEM) shows that defects like pinholes and microvoids are occur in non cryogenic treated samples after wire electric discharge machining. Result shows that surface finish is significantly improved of cryogenic treated samples after wire electric discharge machining.

[Yadav et al., 2012]<sup>15</sup> demonstrates the effect of machining parameters on surface roughness of die steel D3 after WEDM. The input parameters are pulse on time, gap voltage and wire feed rate. These inputs parameters are varied on different levels during experimentation to study its effect on performance characteristic. The surface roughness can be decreases with increase in wire feed rate and good surface finish is obtained at fixed value of pulse on time and gap voltage.

[Alias et al., 2012]<sup>16</sup> analyses the effect of machine feed rate on performance characteristics of wire electric discharge machining like MRR, kerfs width and surface finish. Result shows that machine feed rate is most significant factor that affect the MRR.

[Singh et al., 2013]<sup>17</sup> describes the effect of cryogenic treated wires on machining of die steel D3. The wires are zinc coated diffused brass wire and plain brass wire. The input parameters are pulse width, time between two pulses, wire tension and wire feed rate. The L9 orthogonal array used to design the experiments and after performing the experiments results of both wires are compared. Result shows that MRR is significantly increases with zinc coated diffused brass wire. The increase in MRR is 22.5 % as compared to plain brass wire.

[Kumar et al., 2013]<sup>18</sup> studied the machining of pure titanium by WEDM. In this study the EDS and XRD analysis of machined samples has to be done for investigation of migrate elements on machined surface. Result shows that peak current and pulse on time are significant factors that will affect the surface roughness and wire wear ratio.

[Sharma et al., 2013]<sup>19</sup> evaluate the multi performance characteristics optimization of wire electric discharge machining using response surface methodology. The responses are MRR and surface roughness, results shows that pulse on time is significant factor for surface roughness. The list of experiments is designed by central composite rotatable design (CCRD).

[Lodhi and Agarwal, 2014]<sup>20</sup> optimize the wire electric discharge machining by Taguchi method. The input parameters are pulse on time, pulse off time, peak current and wire feed rate. The

analysis of variance used to check the percent contributions of different factors. Scanning electron micrographs shows the foamy structure after wire electric discharge machining. Peak current is found to be most significant factor affect the surface roughness.

[Kumar et al., 2014]<sup>21</sup> studies the machining of die steel D3 with different electrodes. Different electrodes like brass wire, zinc coated copper wire and steel wire during experimentation. The input parameters of wire electric discharge machine are fixed at some value to check the effect of tools on cutting rate and cutting time. Result shows that maximum cutting rate is occurring with HCS wire as compared to other wires.

[Shivade and Shinde, 2014]<sup>22</sup> demonstrates the wire electric discharge machining of die steel D3 by Taguchi method and grey relational analysis. The input parameters pulse on time, pulse off time, peak current and wire feed rate was varied to check the different responses like MRR, dimensional deviation and gap current. Result shows that current and pulse on time was significant factor that affects the MRR.

[Y. Yildiz et al., 2011]<sup>23</sup> describe the effect of cold and cryogenic treatment on machining of beryllium-copper alloy in electric discharge machining. Results indicated that cold and cryogenic treatment has significant effect on material removal rate.

## **2.1.2 Literature Review about MADM-TOPSIS and AHP Approach**

[R.W Satty, 1987]<sup>24</sup> presented the Analytic Hierarchy Process and explained it with different suitable examples. This paper shows how AHP technique can be applied to different fields with less effort. The fundamental Satty scale used for different fields is also given with suitable definitions.

[Bhangale et al., 2004]<sup>25</sup> describe the selection of robots by MADM-TOPSIS technique. Coding, evaluation and ranking is done with the help of mathematical tools and graphical tools. Different 83 attributes are used to evaluate the robots.

[Chakladar and Chakraborty, 2008]<sup>26</sup> explained the combined TOPSIS-AHP technique for non-conventional machining processes. TOPSIS-AHP method can be used to select the best non-conventional machining process for particular application. This paper also develops the expert

system for non-conventional machining process to apply this technique for further different application in different fields.

[Chia-Chi Sun, 2010]<sup>27</sup> studies the evaluation of performance model by combined TOPSIS and AHP methods. In this paper author explained the techniques with suitable best numerical example of computer companies. The different capabilities of companies of companies are evaluated that will affect the performance.

[Das and Chakraborty, 2011]<sup>28</sup> explained the selection of best non-conventional machining process by analytic network process. By considering different applications the performance of non-traditional machining processes are compared with each other. A computer program is developed in Visual Basics 6.0 with graphical user interface for decision making in non-traditional machining process.

[Sivapirakasam et al., 2011]<sup>29</sup> presented the attribute based decision making for green electric discharge machining. In this paper combined Taguchy and TOPSIS methods used to multi characteristics optimization of green electric discharge machining. By calculating the closeness coefficients of different experiments the best solution can be selected with maximum value of closeness coefficients.

[Kiran et al., 2011]<sup>30</sup> describes the selection of mechatronic system by coding, evaluation and ranking by MADM-TOPSIS technique. In this paper firstly different 83 attributes are identified and then coding, evaluation and ranking done with the help of closeness coefficients. Attributes are analyzed with the help of fishbone diagram.

[R and J.S, 2011]<sup>31</sup> studies the Turning operation optimization of Inconel 718 by using MADM approach. The machining is done with uncarbide cutting tool on Lathe machine. The machining parameters are selected based on relative closeness coefficients.

[Singh and Agrawal, 2012]<sup>32</sup> develop the concurrent design of nanoactuator using MADM approach. Different X-abilities of nanoactuator are evaluated than selection of best design is done with the help of TOPSIS technique. MATLAB can be used to evaluate the TOPSIS technique

[V.S Gadakh, 2012]<sup>33</sup> describe the parametric optimization of WEDM by using TOPSIS method. In this paper author applied the TOPSIS method on experimental data of past researcher and then results of TOPSIS are compared with other optimization techniques.

[Singh and Agrawal, 2014]<sup>34</sup> describes the evaluation of nanomaterial by using MADM approach. Different 96 attributes can be identified, codify and then ranking is done based on mathematical tools and graphical tools. MATLAB Program is used to evaluation of different mathematical approaches.

## **2.2 Identified Gaps in Literature Review**

After a study of different research papers some gaps are found in machining of WEDM. Some of them are discussed below.

- There should be limited work is done for machining of cryogenic treated AISI D3 on WEDM.
- The comparative study on machining of die steel and deep cryogenic treated die steel on WEDM is negligible.
- Performance characteristics affected by process parameters are discussed but effect of parameters on performance are not compared with each other.
- There should be limited work is done for best parameter selection of wire electric discharge machining based on MADAM-TOPSIS methods.
- Very limited work has done for coding, comparison, evaluation, selection and ranking based on attributes for wire EDM.
- The application of combined TOPSIS and AHP methods used for WEDM optimization is limited.

# Chapter 3

## Problem Formulation

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### 3.1 Problem Formulation

After the study there is hardly little information available for machining of deep cryogenic treated die steel by WEDM. The aims of study to check the effect of deep cryogenic treatment on the machining of die steel AISI D3 by wire electric discharge machining. The different input parameters of WEDM are varied to check their effects on output performance characteristics. After machining the Scanning Electron Microscopy (SEM) and Electron Dispersive Spectroscopy (EDS) of selected samples has to be done for check the recast layer and transfer of electrode atoms in the workpiece.

#### 3.1.1 Objectives

The common objectives of this study are discussed below:

- To study the effects of various input parameters on machining before and after deep cryogenic treatment of die steel AISI D3.
- The input parameters are varied on different levels to check its effect on output characteristics like material removal rate, surface roughness and % dimensional deviation.
- To study the Scanning Electron Microscopy (SEM) and Electron Dispersive Spectroscopy (EDS) of selected samples for check the recast layer and diffusion of wire electrode atoms.
- MADAM-TOPSIS and AHP methods are applied to select the optimum parameters setting of wire electric discharge machining.
- The comparative study has to be done on machining of die steel before and after deep cryogenic treatment.
- After machining the cracks and heat affected zone are also studied.

## 3.2 Input and Output Process Parameters

The input parameters are varied on different selected levels to check their effects on performance characteristics. The input parameters are pulse on time, pulse off time, wire feed rate and spark gap set voltage. The output process parameters are material removal rate, surface roughness and % dimensional deviation.

### 3.2.1 Input Process parameters

**Pulse on time** – It is the time during which voltage is applied between the workpiece and electrode. When pulse on time is increased then cutting rate is also increase due to increase in discharge energy. Its unit is microsecond.

**Pulse off time-** It is the duration of time during which no voltage is applied between the electrode and workpiece. In this time re-ionization of dielectric is take place and it strongly affects the cutting rate. Its unit is microsecond.

**Spark gap set voltage-** Spark gap set voltage deals with the voltage applied to gap between the wire and workpiece. When large spark gap voltage is applied then high electric discharge energy is produced in other words cutting rate is increases. Its unit is volts.

**Wire feed rate-** It deals the feed rate of wire through the wire guide path to produce spark. When feed rate is increased then wire consumption is increased so in turn cutting rate is also increased. Its unit is m/min.

### 3.2.2 Output process parameters

**Material removal rate-** The material removal rate is the important performance characteristics. When material removal rate is increased which in turn increase the productivity of industry. It is also defined as the volumetric material removal rate per unit time. It is measured as  $\text{mm}^3/\text{min}$ . The machining different input variables affect the material removal rate.

$$\text{MRR} = \text{cutting speed} \times \text{Height of workpiece} \times \text{width of cut} \quad (3.1)$$

**Surface roughness-** The surface roughness is measured as average surface roughness. It is also defined as deviations on original surface with respect to ideal surface. It can be measured by comparing all peaks and valleys along the mean line. Surface roughness is measured by Mitutoyo SJ 400 profilometer. A stylus can be moved on the surface of workpiece which in turn give the average surface roughness  $R_a$  by comparing all peaks and valleys along the mean line. Its unit is  $\mu\text{m}$ .

**Percentage of Dimensional deviation-** The dimensions of machined samples can be measured with digital vernier calliper. The dimensional deviation is identified as the deviation between the actual and desired dimension of machined sample. The dimensional deviation can be measured as percentage.

$$\text{Percentage of dimensional deviation} = \frac{\text{Observed value} - \text{Actual value}}{\text{Actual value}} \times 100 \quad (3.2)$$

# Chapter 4

## Experimentation

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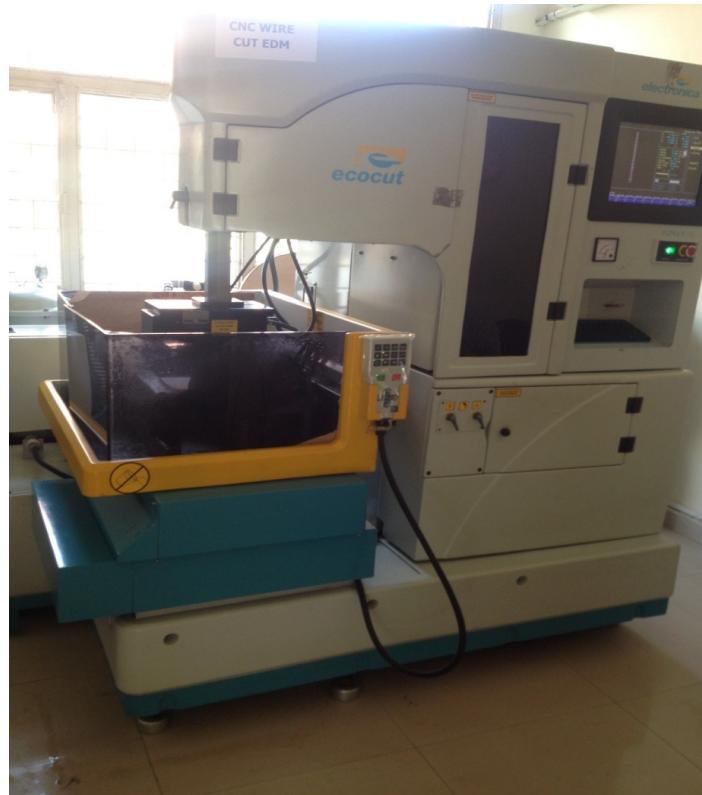
### 4.1 Machine

The Electronica Ecocut Elplus 15 wire EDM machine is used for experimental purpose installed at M.M University Mullana (Ambala). The specifications of machine are discussed below.

**Table 4.1** Electronica Ecocut Wire EDM machine specification

PARAMETERS	SPECIFICATION
Design	Fixed column, moving table
Table size	300 x 350 mm
Maximum workpiece height	200 mm
Maximum workpiece weight	500 kg
Main table traverse(X,Y)	300, 400 mm
Auxiliary table traverse(u,v)	80, 80 mm
Wire electrode diameter	0.25 mm
Controlled axes	XY, U, V Simultaneous/ independent
Interpolation	Linear & circular
Least command input (X, Y, u, v)	0.0005 mm
Input power supply	3 phase, AC 415 V, 50 Hz

The machine has capability to cut complex shapes due to computerized numeric control of machine. The machine components are mechanical section, computerized numeric control, electric discharge power unit and dielectric system. When workpiece is mounted on table of machine and wire can pass through wire guides then spark is produced on machining surface to produce the desired shape. The input parameters are varied by control panel of the machine. When machining is occurring then cutting speed is also shown on control panel screen. The travel path of wire on workpiece is also shown in control panel screen.



**Figure 4.1** Photograph of Electronica Ecocut Elplus 15 wire EDM machine

## 4.2 Workpiece

The AISI D3 die steel plate of 150mm×150mm×10mm before deep cryogenic treatment used for experimental purpose. It is also named as high carbon high chromium steel. The composition of die steel is shown below in table 4.2.

**Table 4.2** Composition of die steel AISI D3

C %	1.56
Si %	0.33
Mn %	0.61
P %	0.02
S %	0.04
Cr %	13.4
Co %	0.01
Ni %	0.10
Fe %	Remaining

### 4.2.1 Deep Cryogenic treated workpiece

The process in which material is cooled below the room temperature is called cryogenic treatment. The treatment in which material is cooled at  $-180^{\circ}\text{C}$  to  $-196^{\circ}\text{C}$  for a period of 18 to 24 hours is called deep cryogenic treatment. The deep cryogenic treated workpiece of size  $80\text{mm}\times 50\text{mm}\times 10\text{mm}$  used for experimental purpose. The liquid nitrogen gas is used for cryogenic treatment. The main advantages of deep cryogenic treatment are :

- Machinability can be improved of hard materials.
- The life of tool components can be increased after treatment.
- Stress can be relieved and improved wear resistance.

### 4.3 Pilot Experimentation

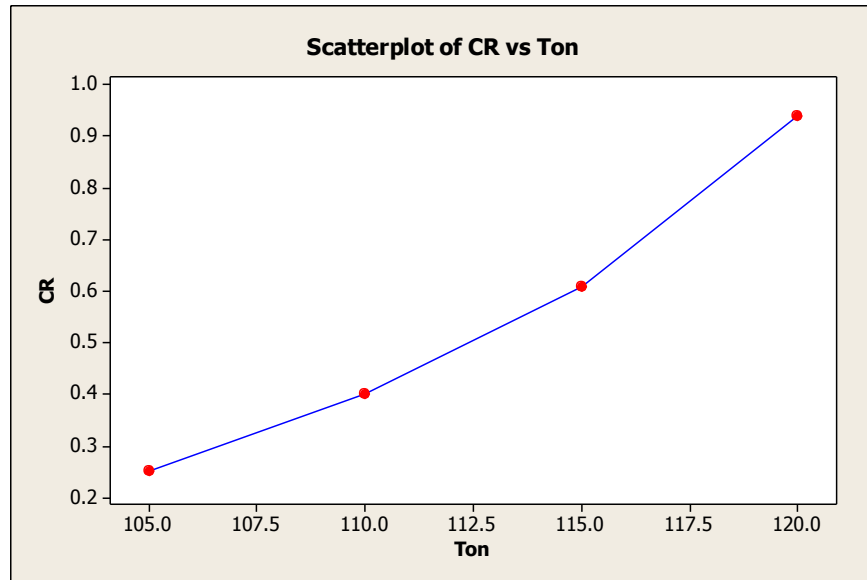
The purpose of this study is analyzing the effect of WEDM process parameters on response variable such as cutting rate. It is used to check the range of different parameters required for experimental design methodology used in this work. The OFAT (one factor at a time) approach is used for vary the different parameters.

#### 4.3.1 Vary pulse on time

The pulse on time is varied from 100 machine units to 131 machine units. The value of other control factors are given as  $T_{\text{off}}=30$  unit and  $IP=12$  A,  $SV=45$  V,  $WT=7$  machine unit,  $WF=6$  m/min and  $SF=2250$  unit. The different values of cutting speed are shown in below Table 4.3. The scatter plot is plotted for different value of pulse on time with respect to cutting rate shown in Figure 4.2.

**Table 4.3** Experimental value of  $T_{\text{on}}$  vs CR

Pulse on time $T_{\text{on}}$	Cutting rate (mm/min)
105	0.25
110	0.40
115	0.61
120	0.94
125	Wire break



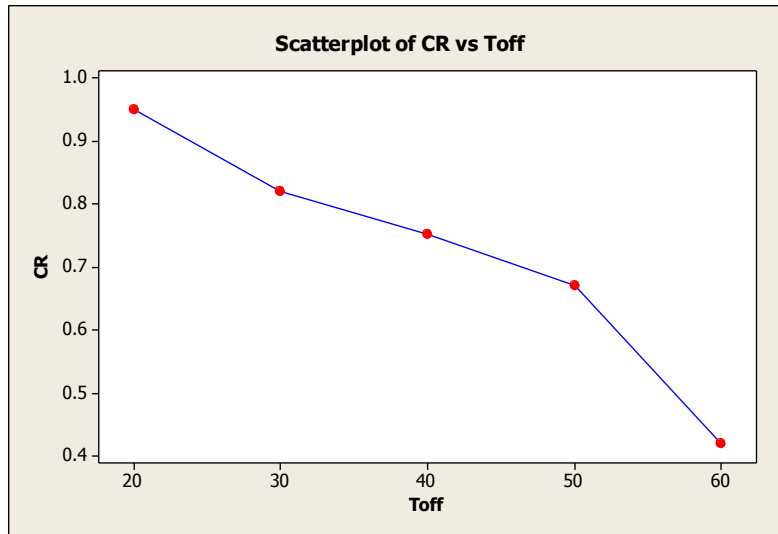
**Figure 4.2** Effect of pulse on time ( $T_{on}$ ) on cutting rate

### 4.3.2 Vary pulse off time

The pulse off time  $T_{off}$  is varied from 0 machine units to 63 machine units. The value of other fixed parameters are given as  $T_{on}=115$  unit,  $IP=12$  A,  $SV=45$  V,  $WT=7$  unit,  $WF=6$  m/min,  $SF=2250$  unit. The cutting rate for different values of pulse off time is shown in Table 4.4. The scatter plot of pulse off time with respect to cutting rate shows that cutting rate is decreased with increase in pulse off time due to decrease in discharge energy. Figure 4.3 indicates the decreasing trend of cutting rate.

**Table 4.4** Experimental value of  $T_{off}$  vs CR

Pulse off time $T_{off}$	Cutting rate (mm/min)
10	Wire break
20	0.95
30	0.82
40	0.75
50	0.67
60	0.42



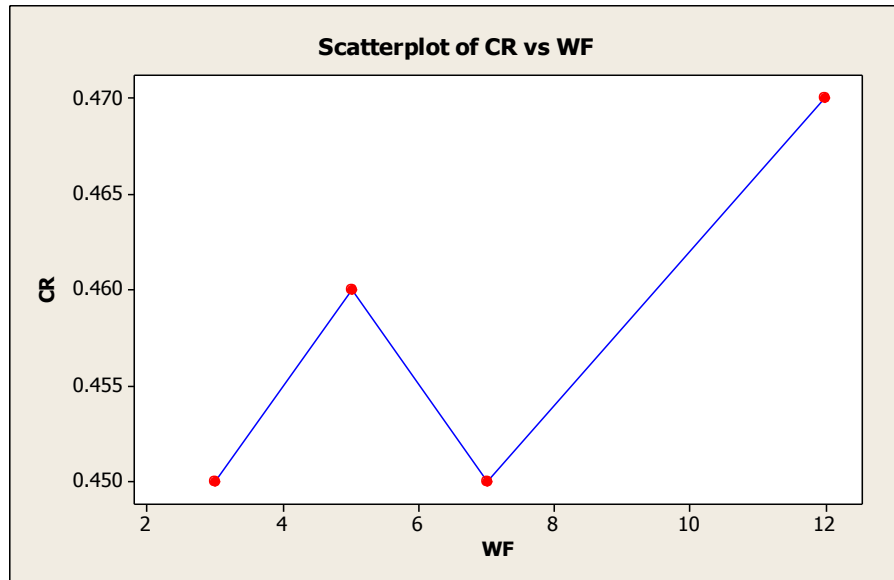
**Fig 4.3** Effect of pulse off time on cutting rate

### 4.3.3 Vary wire feed rate

The range of wire feed rate is 1 m/min to 12 m/min. The value of other fixed parameters are given as  $T_{on}=115$  unit,  $IP=12$  A,  $SV=45$  V,  $WT=7$  unit,  $T_{off}=30$  unit,  $SF= 2250$  unit. The cutting rate for different value of wire feed is shown in Table 4.5. The wire feed rate has limited effect on cutting rate. There is little change in cutting rate with increase in wire feed rate. Figure 4.4 shows the trend of cutting rate with different experimental values of wire feed rate.

**Table 4.5** Experimental value of WF vs CR

Wire feed (m/min)	Cutting Rate (mm/min)
3	0.45
5	0.46
7	0.45
12	0.47



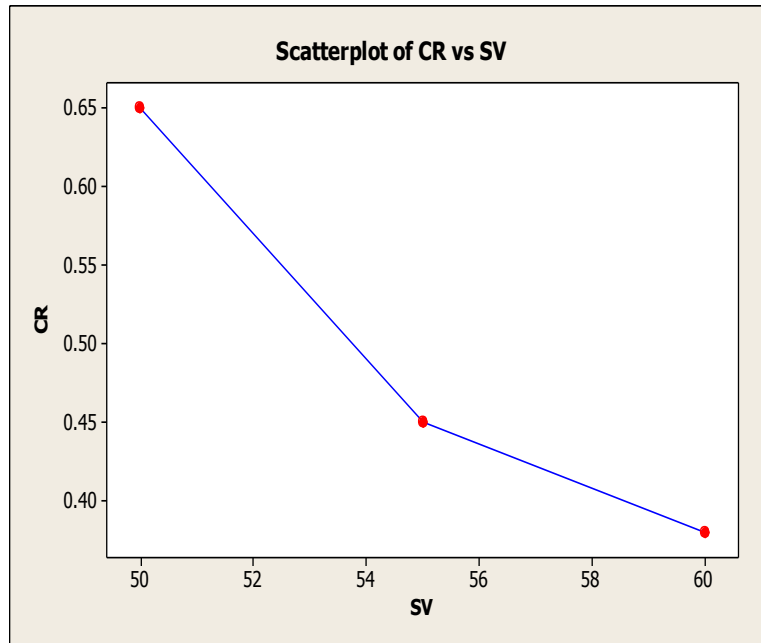
**Figure 4.4** Effect of wire feed rate on Cutting rate

#### 4.3.4 Vary spark gap set voltage

The range of spark gap set voltage is from 0 to 99 V. The spark gap voltage varied from 30 to 60 V. The value of other constant parameters are given as  $T_{on}=115$  unit,  $IP=12$  A,  $WF=6$  m/min,  $WT=7$  unit,  $T_{off}=30$  unit,  $SF= 2250$  unit. The cutting rate for different value of spark gap voltage is shown in Table 4.6. The cutting rate is decreased with increase in spark gap set voltage as shown in Figure 4.5 because when spark gap set voltage is increased then gap between sparks is also increased so less discharge energy is produced.

**Table 4.6** Experimental value of Spark gap voltage vs Cutting rate

Spark gap set voltage (V)	Cutting Rate(mm/min)
30	Wire break
40	Wire break
50	0.65
55	0.45
60	0.38



**Figure 4.5** Effect of spark gap set voltage on cutting rate

#### 4.4 Selection of process parameters ranges

The selection of process parameter ranges is done based on the pilot experimentation. The pilot study indicates the parameter range there is large chances of wire breakage. When pulse on time is varied in pilot study it has been found that wire breakage is occur at 125 unit. So the range of pulse on time is varied from 110 unit to 120 unit. Similarly when pulse off time is varied the chance of wire breakage is decreased with increase in pulse off time. The selection of process parameter ranges shown in Table 4.7 is done based on the data available in pilot experimentation.

**Table 4.7** Process parameters and their ranges

Sr. No.	Process Parameters	Symbols	Range (machine units)	Range (Actual units)
1	Pulse on time	$T_{on}$	110-120	0.6 $\mu$ s-1.1 $\mu$ s
2	Pulse off time	$T_{off}$	50-60	26 $\mu$ s- 46 $\mu$ s
3	Wire feed rate	WF	3-7	m/min
4	Spark gap set voltage	SV	50-60	V

## 4.5 Design of Experiment

Design of experiment is the scientific technique used to perform the experiment efficiently. It is the important statistical tool used to examine the effect of various input parameters on output characteristics. The process of planning of experiments is done by design of experiment. After this quantitative data is collected by performing the experiments and then analyze by examine the effect of various parameters on mean and Analysis of Variance of output characteristics. The common advantages of design of experiment are followed:

- After planning the experiment number of trials to perform the experiments is reduced.
- The variables which hardly affect the performance are identified.
- Optimum setting of parameter is done easily.
- The experimental error is easily found out.

### 4.5.1 Procedure of Experimental Design

The main steps in procedure of experimental design are followed:

- Establishing the objective function.
- Selection of factors.
- Select the number of levels for controllable and uncontrollable factor.
- Calculate the total degree of freedom.
- Select the orthogonal array (OA).
- Assign the factors to columns.
- Perform the experiments according to trial condition in array.
- Analyzing the result.
- Conformation of experiments.

### 4.5.2 Degree of Freedom (DOF)

The total degree of freedom is determined by no. of factors, their interactions and level of factors. The degree of freedom for each factor is given by number of levels minus one.

DOF for each factor= $k-1$

Where k is number of levels for each factor.

### 4.5.3 Selection of Factors

The selection of factor is depends upon the response characteristics. The selection of factors and levels based on the pilot study. The number of factor with different levels shown in Table 4.8. In this experiment set up there are three factors with 3 levels and one factor with 2 levels.

**Table 4.8** Factors with levels and DOF

Factor designation	Factors	LEVELS			DOF
		Level 1	Level 2	Level 3	
A	Spark gap set voltage (SV)	50	60	-	1
B	Pulse on time ( $T_{on}$ )	110	115	120	2
C	Pulse off time ( $T_{off}$ )	50	55	60	2
D	Wire feed (WF)	3	5	7	2

### 4.5.4 SELECTION OF ORTHOGONAL ARRAY

The selection of orthogonal array depends upon:

- The number of factors and interaction of interest.
- The number of levels for the factors of interest.

The total degree of freedom required for experiment explained in below Table 4.9. The number of degree of freedom for factor B, C, D is 2 and for factor A is 1.

**Table 4.9** DOF for factors and interactions

Factors & Interactions	A	B	C	D	A x B	A x C	A x D	Total
DOF	1	2	2	2	2	2	2	13

The total degree of freedom required for experimental data is 13, the orthogonal array to be used should have degree of freedom more than 13. The most suitable OA used for experimental purpose is L18, which has 17 degree of freedom. The additional 4 degree of freedom used for measure the random error. The mixed level L18 Orthogonal Array designed with the help of Minitab 16.0.

**Table 4.10** L18 Design for Experimental Set up

Exp. Trail no.	A	B	C	D
1	50	110	50	3
2	50	110	55	5
3	50	110	60	7
4	50	115	50	3
5	50	115	55	5
6	50	115	60	7
7	50	120	50	5
8	50	120	55	7
9	50	120	60	3
10	60	110	50	7
11	60	110	55	3
12	60	110	60	5
13	60	115	50	5
14	60	115	55	7
15	60	115	60	3
16	60	120	50	7
17	60	120	55	3
18	60	120	60	5

## 4.6 Main Experimentation

Electronica EcoCut Elplus 15 wire EDM machine is used for experimental purpose. The workpieces used for experimentation are die steel AISI D3 of dimensions 150mm×150mm×10mm and deep cryogenic treated die steel AISI D3 of 80mm×50mm×10mm. A punch of 5mm×5mm×10mm can be cut into the workpiece. The workpiece is fixed on machining table as shown in Figure 4.6. The workpiece during machining is shown in Figure 4.7.



**Figure 4.6** Photographic view of workpiece fixed on machining table



**Figure 4.7** Photographic view of workpiece during machining

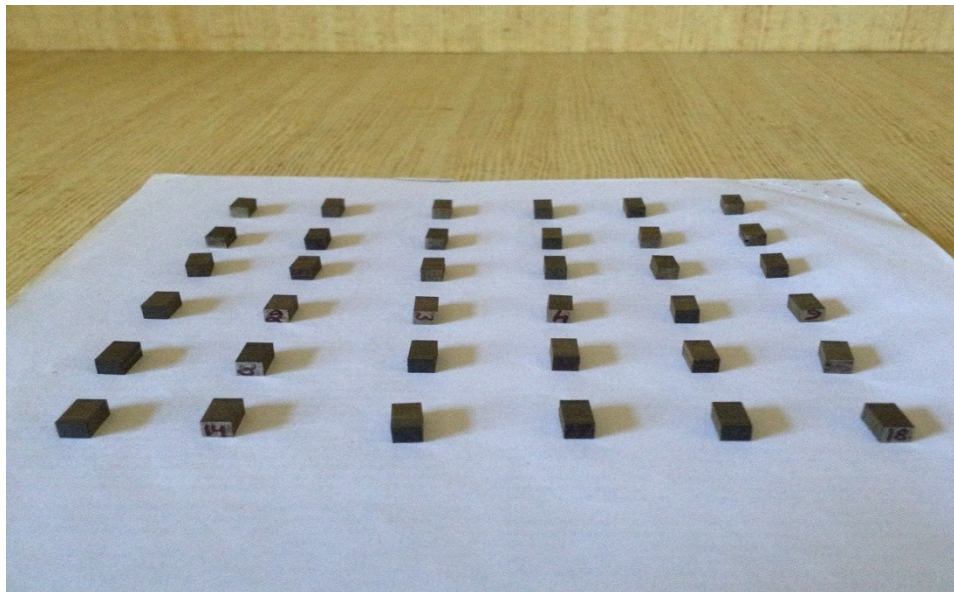
The parameters of machine which are fixed during experimentation shown in Table 4.11. The experiments trials are performed according to the L18 Orthogonal Array. The performance characteristics are calculated by using methodology discussed in section 3.2.2.

**Table 4.11** Fixed parameters during Experimentation.

Sr. No.	Machining parameters	Units	Fixed values
1.	Electrode material	—	Brass(Ø 0.25mm)
2.	Electrode polarity	—	Negative
3.	Dielectric fluid	—	Deionized water
4.	Peak current	A	12
5.	Wire tension	gram	850
6.	Servo feed	—	2250
7.	Dielectric pressure	Kg/cm <sup>2</sup>	7

#### 4.6.1 Preparation of Specimen

The workpice is fixed on table then punch of size 5mm×5mm×10mm cut into the workpice during each experiment. The cut out specimen from workpice are shown in figure 4.8.



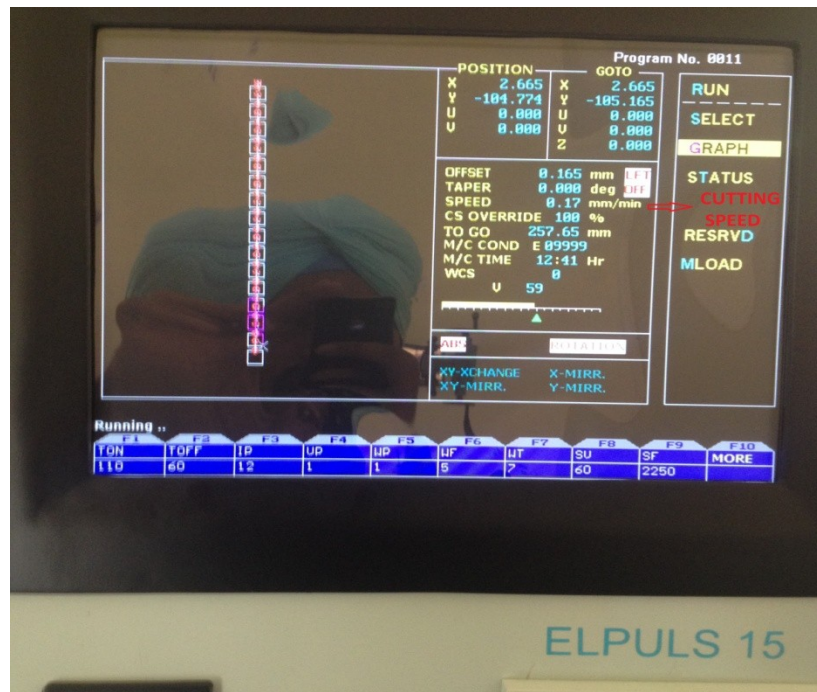
**Figure 4.8** Photographic view of cut out specimen from workpice

## 4.6.2 Performance characteristics

**Material Removal Rate-** It is defined as the amount of volumetric material removal per unit time. It is measured in  $\text{mm}^3/\text{min}$ . It can be high as possible to increase the productivity of industry. It is denoted by MRR. It is calculated by this mathematical formula:

$$\text{MRR} = \text{cutting speed} \times \text{thickness of workpiece} \times \text{width of cut} \quad (4.1)$$

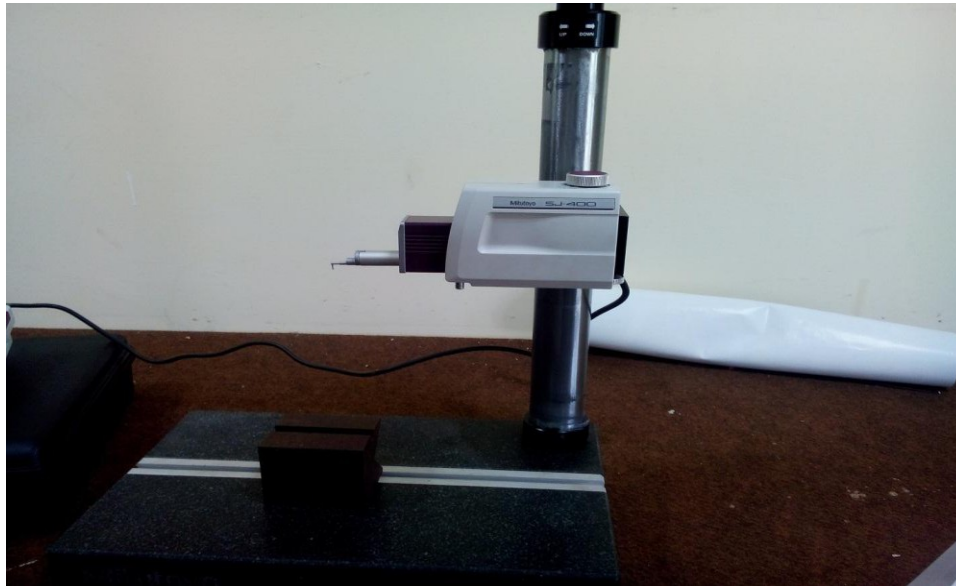
The cutting speed is displayed on screen of control panel during machining as shown in figure 4.9. The thickness of workpiece is 10 mm during each experiment.



**Figure 4.9** Photographic view of cutting speed displayed on screen

**SURFACE ROUGHNESS-** The most commonly measured surface roughness as the average surface roughness and it is denoted by  $R_a$ . The average surface roughness is measured by comparison of peak and valleys along the mean line. In this study surface roughness is measured by Mitutoyo SJ 400 Profilometer as shown in figure 4.10. When stylus is moved on the

machined surface then  $R_a$  is displayed on screen of surface roughness tester. It is measured in  $\mu\text{m}$ .



**Figure 4.10** Photographic view of surface roughness tester Mitutoyo SJ 400

**Percentage of Dimensional Deviation-** Dimensional deviation is defined as the deviation between the desired and actual dimension. The dimension of specimen is measured by digital vernier caliper shown in figure 4.11. The dimensional deviation is measured as percentage by using this mathematical expression:

$$\% \text{ Dimensional deviation} = \frac{\text{Observed value} - \text{Actual value}}{\text{Actual value}} \times 100 \quad (4.2)$$



**Figure 4.11** Photographic view of digital vernier calliper

### 4.6.3 Experimental Results of Die Steel AISI D3

The experiments are performed by using L18 orthogonal array to study the effect of input parameters and their interactions on output characteristics. The experimental results of die steel AISI D3 for performance characteristics shown in Table 4.12 to 4.14. Each experiment can be repeated twice for calculate the S/N ratio.

**Table 4.12** Experimental results of die steel AISI D3 for material removal rate

Exp. No.	Pulse on time (T <sub>on</sub> )	Pulse off time (T <sub>off</sub> )	Spark gap set voltage (SV)	Wire feed rate (WF)	MRR(mm <sup>3</sup> /min)		Mean	S/N Ratio
					Trial 1	Trial 2		
1.	110	50	50	3	1.283	1.280	1.2795	2.1408
2.	110	55	50	5	1.152	0.916	0.9150	-0.7715
3.	110	60	50	7	0.891	0.726	0.7245	-2.7992
4.	115	50	50	3	2.201	1.727	1.7280	4.7508
5.	115	55	50	5	1.741	1.259	1.2585	1.9970
6.	115	60	50	7	1.390	1.055	1.0530	0.4485
7.	120	50	50	5	3.320	2.528	2.5265	8.0503
8.	120	55	50	7	2.474	1.835	1.8335	5.2656
9.	120	60	50	3	1.950	1.625	1.6235	4.2090
10.	110	50	60	7	1.010	0.762	0.7610	-2.3723
11.	110	55	60	3	0.719	0.595	0.5970	-4.4806
12.	110	60	60	5	0.514	0.494	0.4935	-6.1342
13.	115	50	60	5	1.115	1.137	1.1380	1.1228
14.	115	55	60	7	0.966	0.864	0.8620	-1.2899
15.	115	60	60	3	0.822	0.706	0.7050	-3.0362
16.	120	50	60	7	2.331	2.208	2.2065	6.8740
17.	120	55	60	3	1.620	1.437	1.4355	3.1400
18.	120	60	60	5	1.316	0.985	0.9830	-0.1489

**Table 4.13** Experimental results of die steel AISI D3 for surface roughness

Exp. No.	Pulse on time ( $T_{on}$ )	Pulse off time ( $T_{off}$ )	Spark gap set voltage (SV)	Wire feed rate (WF)	Surface Roughness $R_a(\mu\text{m})$		Mean	S/N Ratio
					Trial 1	Trial 2		
1.	110	50	50	3	1.04	1.05	1.045	-0.3824
2.	110	55	50	5	1.01	1.01	1.010	-0.0864
3.	110	60	50	7	1.04	1.05	1.045	-0.3824
4.	115	50	50	3	1.17	1.16	1.165	-1.3266
5.	115	55	50	5	1.16	1.18	1.170	-1.3640
6.	115	60	50	7	1.11	1.10	1.105	-0.8673
7.	120	50	50	5	1.26	1.28	1.270	-2.0763
8.	120	55	50	7	1.29	1.30	1.295	-2.2454
9.	120	60	50	3	1.23	1.25	1.240	-1.8687
10.	110	50	60	7	0.97	0.96	0.965	0.3093
11.	110	55	60	3	0.89	0.90	0.895	0.9634
12.	110	60	60	5	0.83	0.85	0.840	1.5138
13.	115	50	60	5	0.99	0.97	0.980	0.1750
14.	115	55	60	7	1.30	1.32	1.310	-2.3456
15.	115	60	60	3	0.97	0.99	0.980	0.1750
16.	120	50	60	7	1.21	1.23	1.220	-1.7274
17.	120	55	60	3	1.03	1.01	1.020	-0.1724
18.	120	60	60	5	0.99	0.98	0.985	0.1311

**Table 4.14** Experimental results of die steel AISI D3 for percentage of dimensional deviation

Exp. No.	Pulse on time (T <sub>on</sub> )	Pulse off time (T <sub>off</sub> )	Spark gap set voltage (SV)	Wire feed rate (WF)	Percentage of dimensional deviation		Mean	S/N Ratio
					Trial 1	Trial 2		
1.	110	50	50	3	0.54	0.55	0.545	5.271
2.	110	55	50	5	0.14	0.14	0.140	17.077
3.	110	60	50	7	0.47	0.46	0.465	6.650
4.	115	50	50	3	0.62	0.60	0.610	4.292
5.	115	55	50	5	0.25	0.26	0.255	11.867
6.	115	60	50	7	0.36	0.35	0.355	8.994
7.	120	50	50	5	0.95	0.93	0.940	0.537
8.	120	55	50	7	0.20	0.21	0.205	13.762
9.	120	60	50	3	0.34	0.36	0.350	9.115
10.	110	50	60	7	0.47	0.47	0.470	6.558
11.	110	55	60	3	0.29	0.30	0.295	10.602
12.	110	60	60	5	0.35	0.37	0.360	8.870
13.	115	50	60	5	0.60	0.62	0.610	4.292
14.	115	55	60	7	0.24	0.23	0.235	12.576
15.	115	60	60	3	0.17	0.19	0.180	14.881
16.	120	50	60	7	0.58	0.60	0.590	4.581
17.	120	55	60	3	0.24	0.25	0.245	12.214
18.	120	60	60	5	0.15	0.17	0.160	15.900

#### 4.6.4 Experimental Results of Deep Cryogenic Treated Die Steel AISI D3

The parameters setting for machining of deep cryogenic treated die steel are similar to non cryogenic treated die steel. In this different input parameters are varied to check their effect on performance characteristics. Experimental results for deep cryogenic treated die steel are shown in Table 4.15 to 4.17.

**Table 4.15** Experimental results of deep cryogenic treated die steel AISI D3 for MRR

Exp. No.	Pulse on time (T <sub>on</sub> )	Pulse off time (T <sub>off</sub> )	Spark gap set voltage (SV)	Wire feed rate (WF)	MRR(mm <sup>3</sup> /min)		Mean	S/N Ratio
					Trial 1	Trial 2		
1.	110	50	50	3	1.283	1.286	1.2845	2.1747
2.	110	55	50	5	1.152	1.155	1.1535	1.2403
3.	110	60	50	7	0.891	0.894	0.8925	-0.9879
4.	115	50	50	3	2.201	2.205	2.2030	6.8603
5.	115	55	50	5	1.741	1.744	1.7425	4.8234
6.	115	60	50	7	1.390	1.390	1.3900	2.8603
7.	120	50	50	5	3.320	3.319	3.3195	10.4215
8.	120	55	50	7	2.474	2.476	2.4750	7.8715
9.	120	60	50	3	1.950	1.952	1.9510	5.8051
10.	110	50	60	7	1.010	1.012	1.0110	0.0950
11.	110	55	60	3	0.719	0.716	0.7175	-2.8836
12.	110	60	60	5	0.514	0.510	0.5120	-5.8148
13.	115	50	60	5	1.115	1.118	1.1165	0.9572
14.	115	55	60	7	0.966	0.968	0.9670	-0.2915
15.	115	60	60	3	0.822	0.825	0.8235	-1.6868
16.	120	50	60	7	2.331	2.330	2.3305	7.3490
17.	120	55	60	3	1.620	1.625	1.6225	4.2037
18.	120	60	60	5	1.283	1.286	1.3175	2.3950

**Table 4.16** Experimental results of deep cryogenic treated die steel AISI D3 for surface roughness

Exp. No.	Pulse on time ( $T_{on}$ )	Pulse off time ( $T_{off}$ )	Spark gap set voltage (SV)	Wire feed rate (WF)	Surface Roughness $R_a(\mu m)$		Mean	S/N Ratio
					Trial 1	Trial 2		
1.	110	50	50	3	1.55	1.57	1.560	-3.8626
2.	110	55	50	5	1.48	1.50	1.490	-3.4639
3.	110	60	50	7	1.45	1.43	1.440	-3.1674
4.	115	50	50	3	1.70	1.73	1.715	-4.6856
5.	115	55	50	5	1.64	1.62	1.630	-4.2439
6.	115	60	50	7	1.60	1.60	1.600	-4.0824
7.	120	50	50	5	2.10	2.11	2.105	-6.4650
8.	120	55	50	7	1.95	1.96	1.955	-5.8229
9.	120	60	50	3	1.80	1.78	1.790	-5.0572
10.	110	50	60	7	1.42	1.45	1.435	-3.1375
11.	110	55	60	3	1.36	1.35	1.355	-2.6388
12.	110	60	60	5	1.20	1.22	1.210	-1.6560
13.	115	50	60	5	1.50	1.52	1.510	-3.5797
14.	115	55	60	7	1.57	1.59	1.580	-3.9733
15.	115	60	60	3	1.48	1.46	1.470	-3.3465
16.	120	50	60	7	2.11	2.14	2.125	-6.5474
17.	120	55	60	3	1.95	1.98	1.965	-5.8675
18.	120	60	60	5	1.70	1.69	1.695	-4.5834

**Table 4.17** Experimental results of deep cryogenic treated die steel AISI D3 for percentage of dimensional deviation

Exp. No.	Pulse on time (T <sub>on</sub> )	Pulse off time (T <sub>off</sub> )	Spark gap set voltage (SV)	Wire feed rate (WF)	Percentage of dimensional deviation		Mean	S/N Ratio
					Trial 1	Trial 2		
1.	110	50	50	3	0.51	0.52	0.515	5.7634
2.	110	55	50	5	0.10	0.11	0.105	19.5664
3.	110	60	50	7	0.45	0.45	0.450	6.9357
4.	115	50	50	3	0.59	0.57	0.580	4.7301
5.	115	55	50	5	0.23	0.22	0.225	12.9542
6.	115	60	50	7	0.34	0.34	0.340	9.3704
7.	120	50	50	5	0.91	0.90	0.905	0.8669
8.	120	55	50	7	0.16	0.18	0.170	15.3760
9.	120	60	50	3	0.32	0.30	0.310	10.1682
10.	110	50	60	7	0.45	0.44	0.445	7.0323
11.	110	55	60	3	0.27	0.25	0.260	11.6941
12.	110	60	60	5	0.33	0.35	0.340	9.3667
13.	115	50	60	5	0.58	0.60	0.590	4.5817
14.	115	55	60	7	0.21	0.19	0.200	13.9686
15.	115	60	60	3	0.15	0.15	0.150	16.4782
16.	120	50	60	7	0.56	0.55	0.555	5.1138
17.	120	55	60	3	0.22	0.21	0.215	13.3489
18.	120	60	60	5	0.51	0.52	0.120	18.3863

# Chapter 5

## Analysis and Discussion of Results

### 5.1 Analysis and Discussion of Results for die steel AISI D3

After performing the experiments the analysis of results has to be done by calculate the S/N ratio and mean value of experimental results. The main effect and interaction plots are drawn to study the effect of process parameters on performance characteristics. The analysis of variance (ANOVA) has to be done to find the significant factors.

#### 5.1.1 Effect on Material Removal Rate

The experimental results of material removal rate are shown in table 4.12. Based on these results the mean plots are drawn for average data and S/N ratio shown in figure 5.1 and 5.2 below. The interaction plots for average and S/N ratio are shown in figure 5.3 and 5.4. It has been found that material removal rate is increases with increase in pulse on time and decreases with increase in spark gap set voltage and pulse off time.

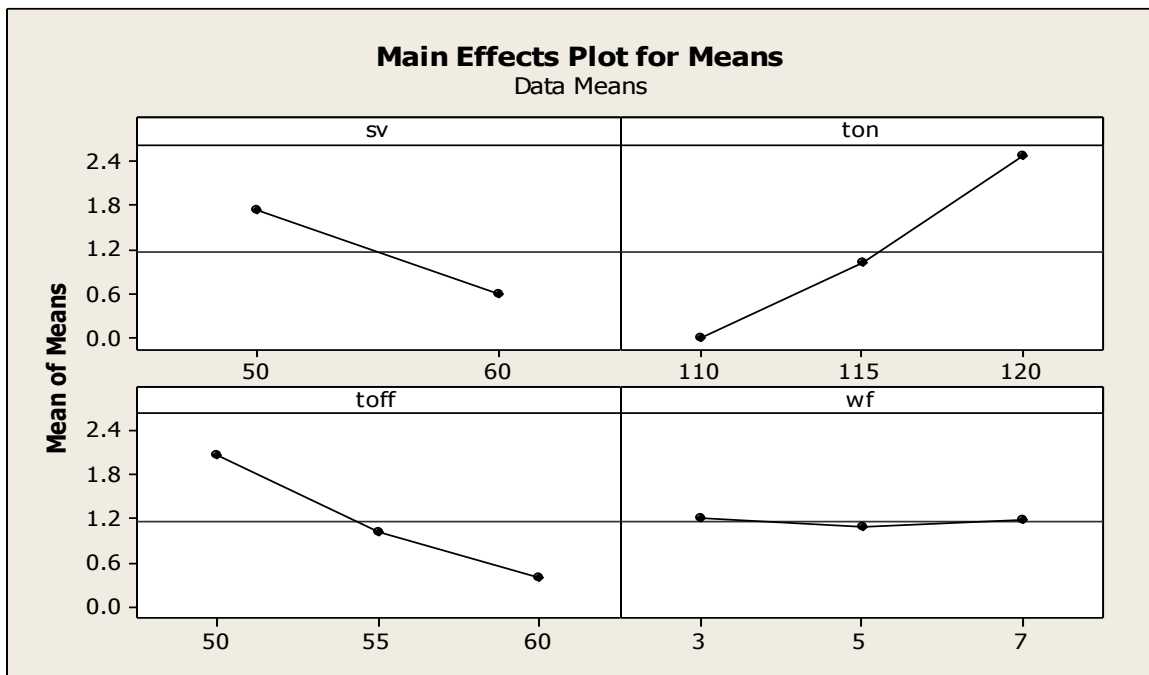
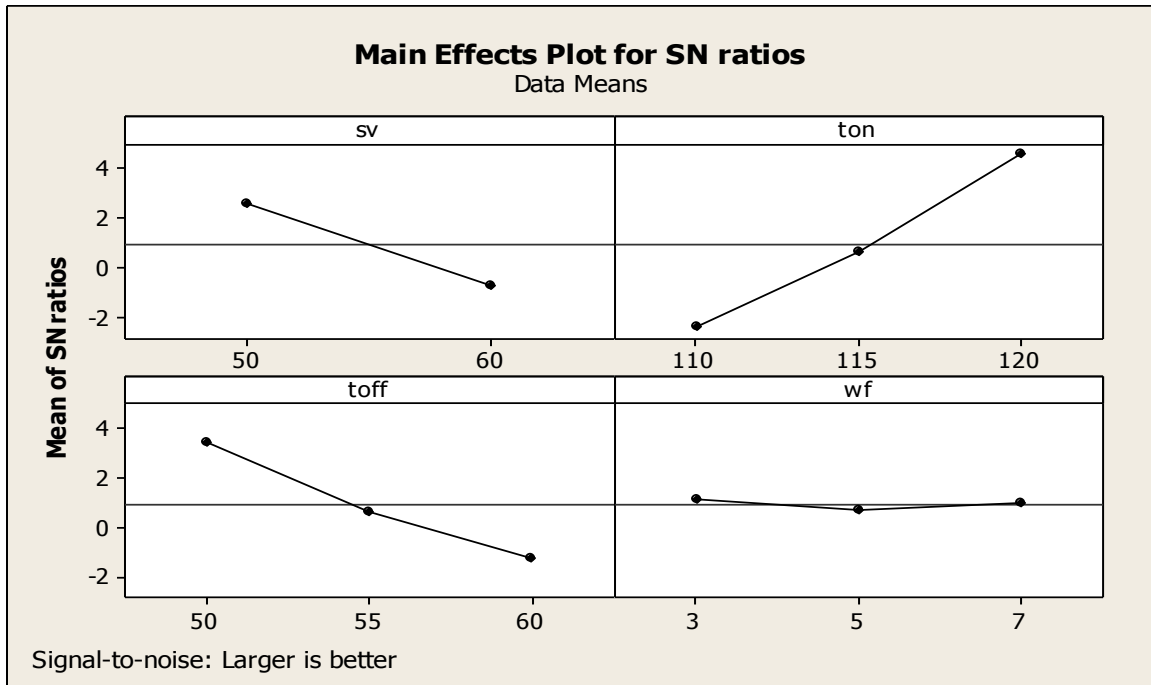
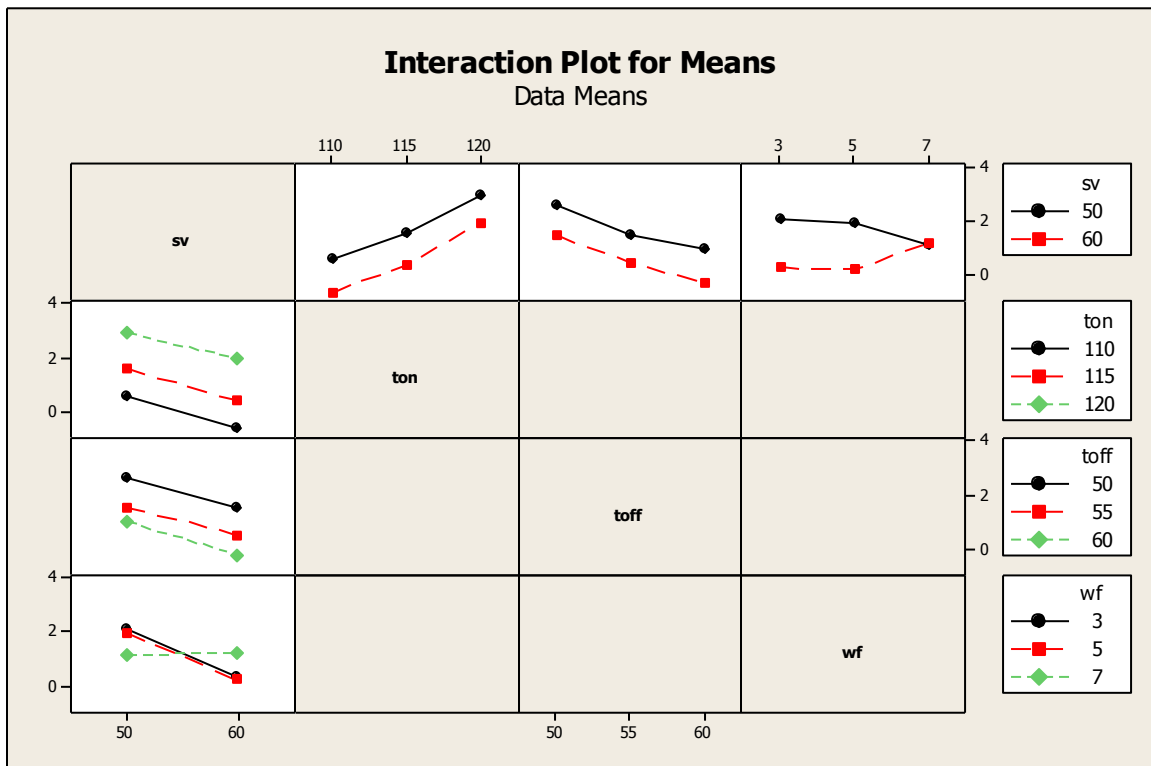


Figure 5.1 Effect of process parameters on MRR (Mean Data)



**Figure 5.2** Effect of process parameters on MRR (S/N Ratio)



**Figure 5.3** Effect of process parameter Interactions on MRR (Mean Data)



**Figure 5.4** Effect of process parameter Interactions on MRR (Mean Data)

The analysis of variance for material removal rate has to be done for mean data shown in table 5.1. It has been found that spark gap set voltage, pulse on time and pulse off time are significant factors based on value of P table i.e. less than 0.05.

**Table 5.1** Analysis of variance for MRR (Mean data)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SV	1	0.78563	0.78563	0.78563	13.19	0.022 *
T <sub>on</sub>	2	2.93941	2.93941	1.46971	24.67	0.006 *
T <sub>off</sub>	2	1.42754	0.94342	0.47171	7.92	0.041 *
WF	2	0.00133	0.00785	0.00392	0.07	0.937
SV×T <sub>on</sub>	2	0.00870	0.00870	0.00435	0.07	0.931
SV×T <sub>off</sub>	2	0.01513	0.01513	0.00756	0.13	0.884
SV×WF	2	0.06065	0.06065	0.03032	0.51	0.635
Error	4	0.23831	0.23831	0.05958		
Total	17	5.47669				

\*Significant at 95 % Confidence Level

The analysis of variance for material removal rate has to be done for S/N ratio shown in table 5.2. The results showed that spark gap set voltage, pulse on time and pulse off time are significant factors at 95% level of confidence. The response table for mean data and S/N ratio are shown in table 5.3 and 5.4 respectively. The ranks are assigned to different parameters based on delta value. The highest value of delta gives the highest rank to the process parameter. The meaning of highest rank is that the process parameter has high relative importance towards the performance characteristics.

**Table 5.2** Analysis of variance for MRR (S/N Data)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SV	1	48.731	48.731	48.731	70.40	0.001 *
T <sub>on</sub>	2	146.346	146.346	73.173	105.70	0.000 *
T <sub>off</sub>	2	66.269	40.652	20.326	29.36	0.004 *
WF	2	0.623	0.440	0.220	0.32	0.745
SV×T <sub>on</sub>	2	1.335	1.335	0.668	0.96	0.455
SV×T <sub>off</sub>	2	0.246	0.246	0.123	0.18	0.843
SV×WF	2	0.327	0.327	0.164	0.24	0.800
Error	4	2.769	2.769	0.692		
Total	17	266.647				

\*Significant at 95 % Confidence Level

**Table 5.3** Response table for MRR (Mean Data)

Level	SV	T <sub>on</sub>	T <sub>off</sub>	WF
1	1.72548	-0.00441	2.06188	1.20122
2	0.58942	1.00944	1.02354	1.08579
3		2.46732	0.38693	1.18534
Delta	1.13607	2.47173	1.67495	0.11543
Rank	3	1	2	4

**Table 5.4** Response table for MRR (S/N Ratio)

Level	SV	T <sub>on</sub>	T <sub>off</sub>	WF
1	2.5879	-2.4029	3.4278	1.1207
2	-0.7028	0.6655	0.6434	0.6859
3		4.5650	-1.2435	1.0211
Delta	3.2908	6.9679	4.6713	0.4347
Rank	3	1	2	4

### 5.1.2 Effect on Surface Roughness

The experimental results of performed experiments for surface roughness are shown in table 4.13. Based on these results the mean plots are drawn for average data and S/N ratio shown in figure 5.5 and 5.6 respectively. It has been found that surface roughness is increase with increase in pulse on time because when pulse on time is increased than large sparks of energy are produced the craters on machined surface. The interactions plots of process parameters for average mean data and S/N ratio are shown in figure 5.7 and 5.8 respectively. The main effect plot for mean data shows that surface roughness is decreases with increase in spark gap set voltage due to decrease in discharge energy.

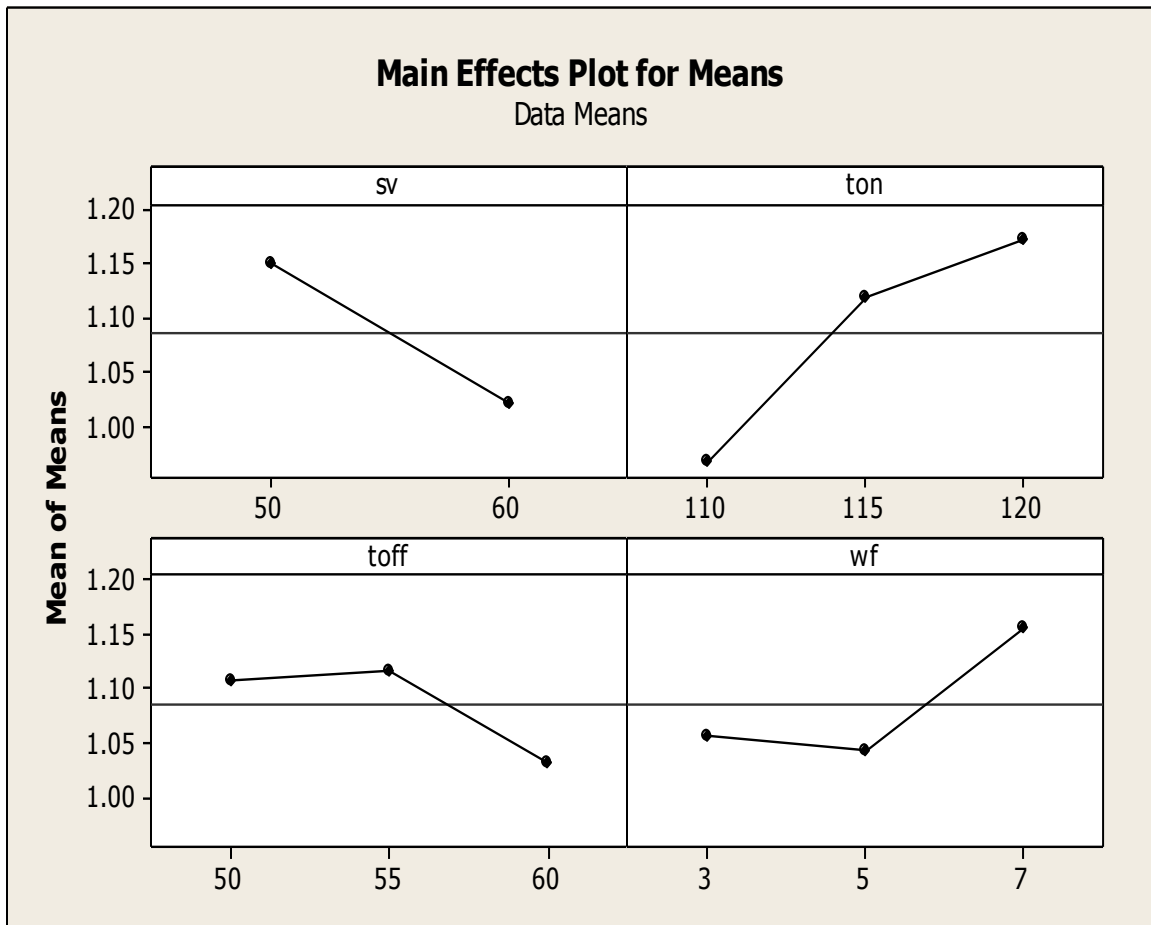
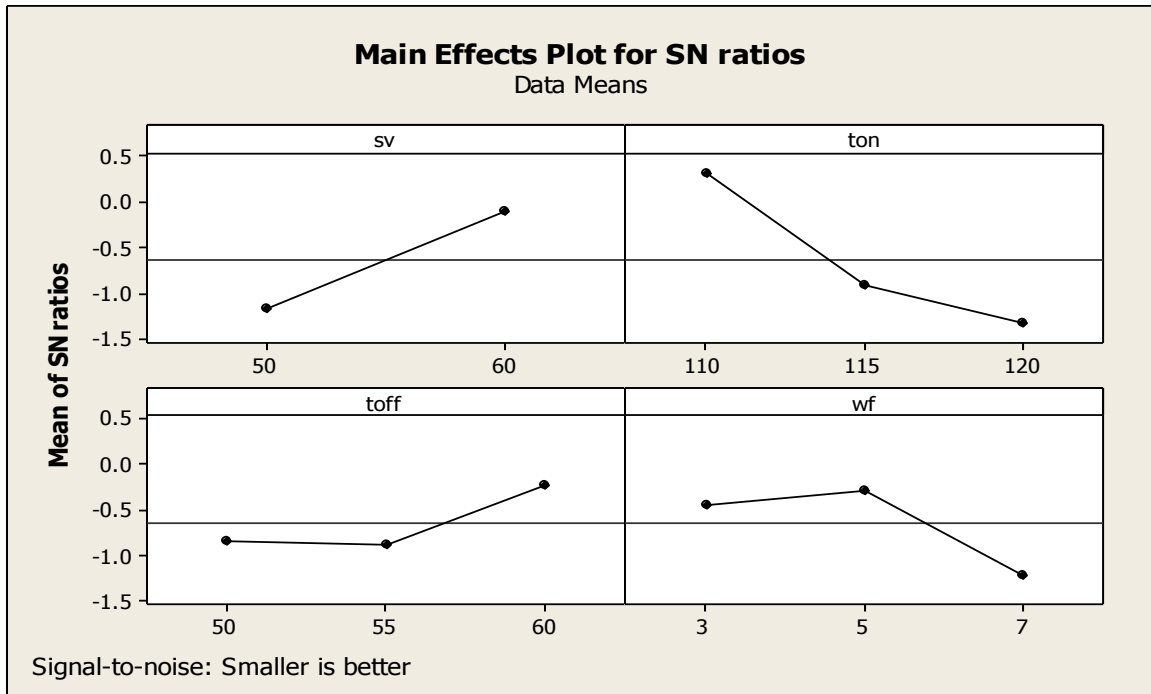
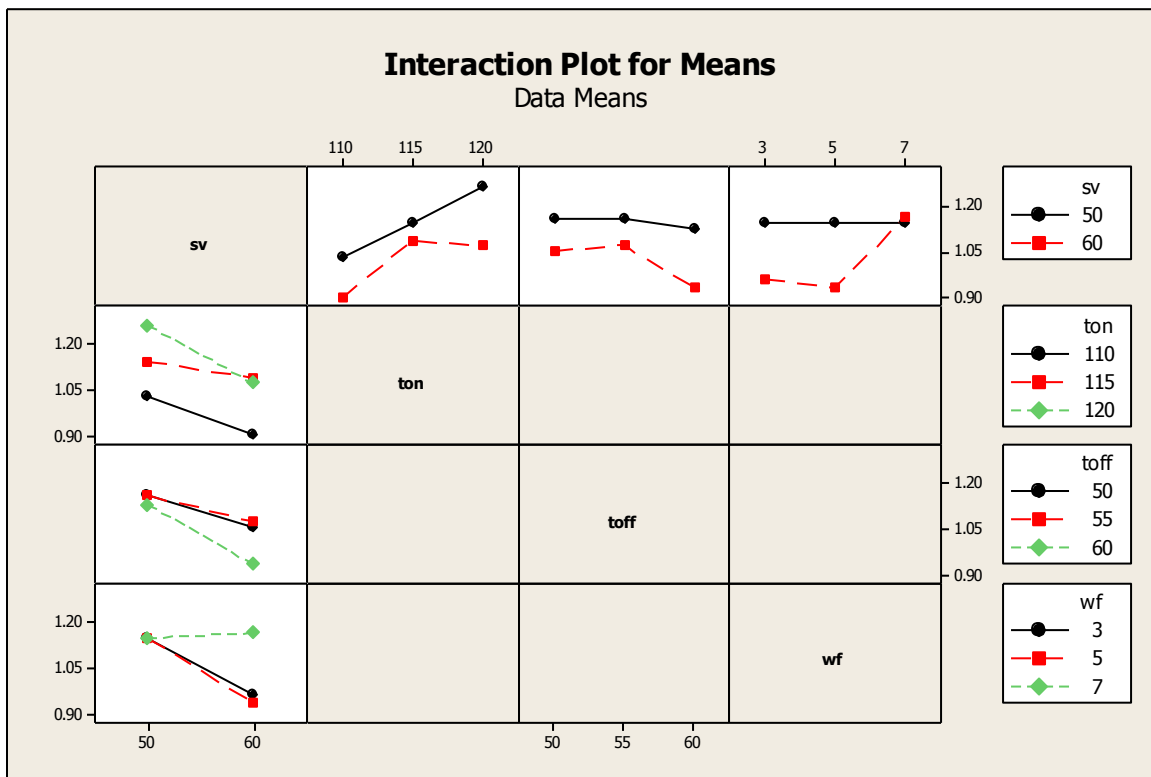


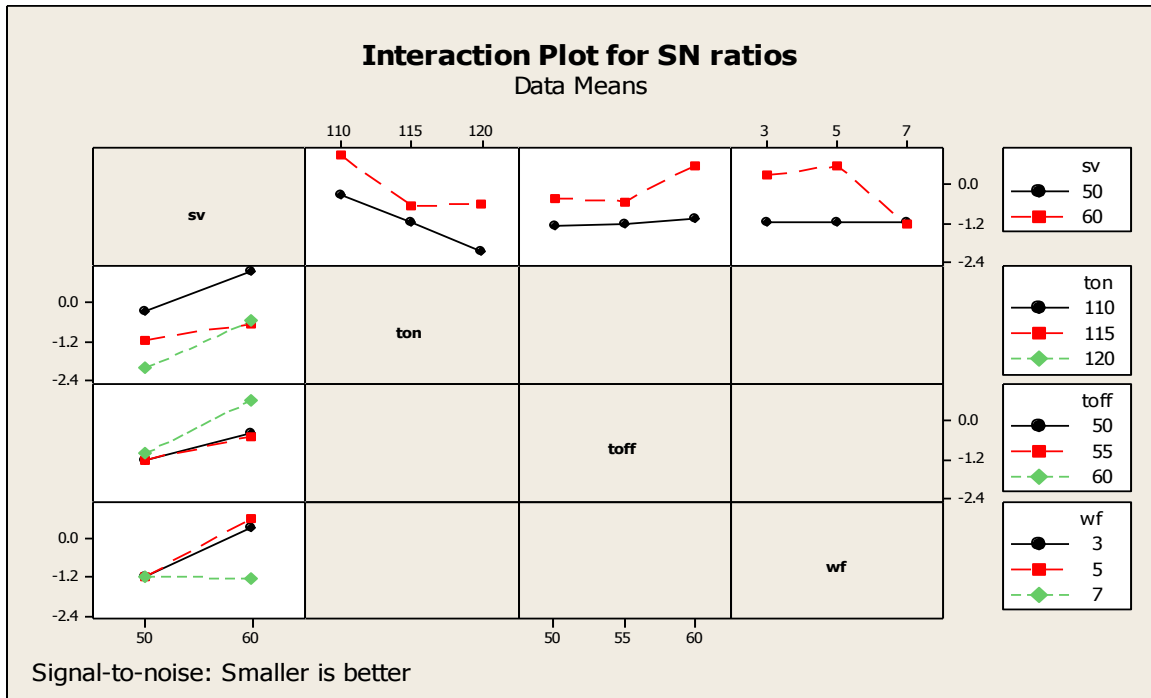
Figure 5.5 Effect of process parameter on surface roughness (Mean Data)



**Figure 5.6** Effect of process parameters on surface roughness (S/N Ratio)



**Figure 5.7** Effect of process parameter interactions on surface roughness (Mean Data)



**Figure 5.8** Effect of process parameter interactions on surface roughness (S/N Ratio)

The analysis of variance for surface roughness has to be done for mean data and S/N ratio is shown in table 5.5 and 5.6 respectively. Results show that spark gap set voltage, pulse on time, wire feed rate are significant factors at 95% level of confidence. The interaction of spark gap set voltage and wire feed rate are also significant shown in table 5.5 and 5.6.

**Table 5.5** Analysis of variance for surface roughness (Mean data)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SV	1	0.073472	0.073472	0.073472	39.54	0.003 *
T <sub>on</sub>	2	0.135744	0.135744	0.067872	36.52	0.003 *
T <sub>off</sub>	2	0.025586	0.009239	0.004619	2.49	0.199
WF	2	0.046186	0.042739	0.021369	11.50	0.022 *
SV×T <sub>on</sub>	2	0.014078	0.014078	0.007039	3.79	0.119
SV×T <sub>off</sub>	2	0.007072	0.007072	0.003536	1.90	0.263
SV×WF	2	0.031272	0.031272	0.015636	8.41	0.037 *
Error	4	0.007433	0.007433	0.001858		
Total	17	0.340844				

\*Significant at 95 % Confidence Level

**Table 5.6** Analysis of variance for surface roughness (S/N Ratio)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SV	1	5.1451	5.1451	5.1451	54.88	0.002*
T <sub>on</sub>	2	8.8754	8.8754	4.4377	47.33	0.002*
T <sub>off</sub>	2	1.6438	0.4818	0.2409	2.57	0.192
WF	2	2.9588	2.5411	1.2706	13.55	0.017*
SV×T <sub>on</sub>	2	0.7275	0.7275	0.3638	3.88	0.116
SV×T <sub>off</sub>	2	0.3451	0.3451	0.1725	1.84	0.271
SV×WF	2	1.9124	1.9124	0.9562	10.20	0.027*
Error	4	0.3750	0.3750	0.0938		
Total	17	21.9831				

\*Significant at 95 % Confidence Level

The response tables for mean data and S/N ratio are drawn shown in table 5.7 and 5.8 respectively. The ranking of process parameters has to be done based on delta value. Result shows that pulse on time is highly relative important factor for surface roughness. The delta value shows that surface roughness is greatly affected by pulse on time followed by spark gap set voltage, wire feed rate and pulse off time.

**Table 5.7** Response table for Surface Roughness (Mean Data)

Level	SV	T <sub>on</sub>	T <sub>off</sub>	WF
1	1.1494	0.9667	1.1075	1.0575
2	1.0217	1.1183	1.1167	1.0425
3		1.1717	1.0325	1.1567
Delta	0.1278	0.2050	0.0842	0.1142
Rank	2	1	4	3

**Table 5.8** Response table for Surface Roughness (S/N Ratio)

Level	SV	T <sub>on</sub>	T <sub>off</sub>	WF
1	-1.1776	0.3227	-0.8379	-0.4350
2	-0.1083	-0.9253	-0.8749	-0.2842
3		-1.3263	-0.2161	-1.2097
Delta	1.0693	1.6490	0.6588	0.9255
Rank	2	1	4	3

### 5.1.3 Effect on Percentage of Dimensional deviation

The experimental results of performed experiments for % dimensional deviation are shown in table 4.14. The mean effect plots for mean data and S/N ratio are drawn shown in figure 5.9 and 5.10 respectively. Figure 5.9 shows that dimensional deviation decreases with increase in spark gap set voltage. When pulse on time is increased the dimensional deviation firstly decreases then slightly increases. With increase in pulse off time the dimensional deviation firstly decreases then increases as shown in figure 5.9. The interactions plots for mean data and S/N ratio are shown 5.11 and 5.12 respectively. The effect of wire feed rate on percentage of dimensional deviation is not clearly seen.

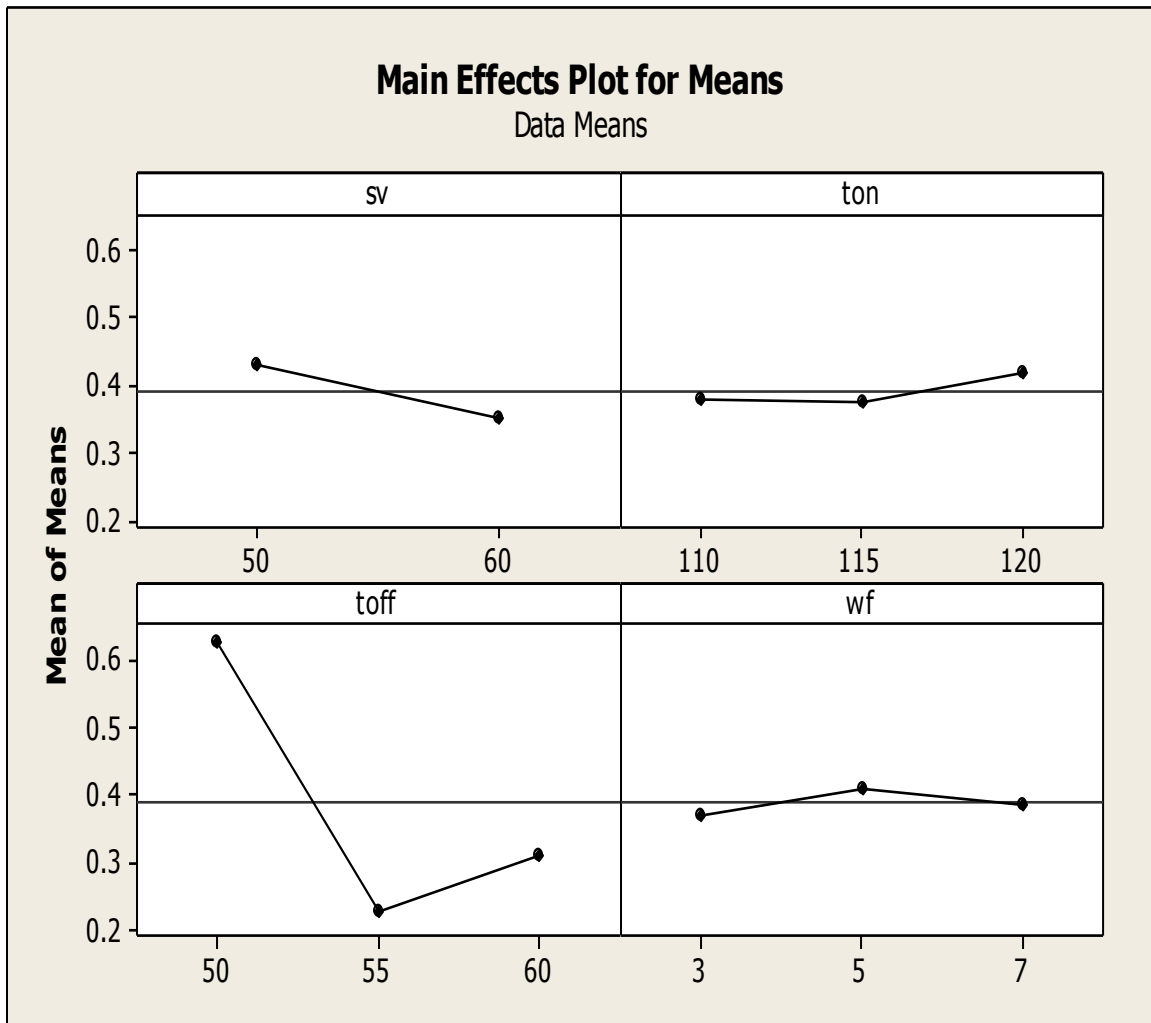
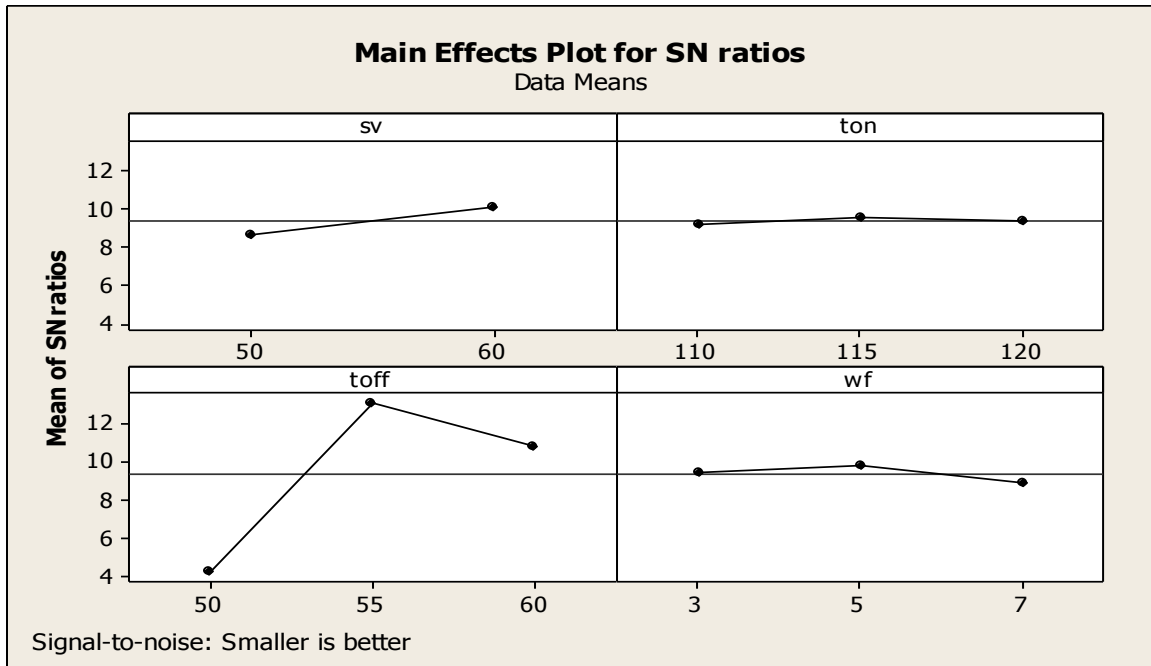
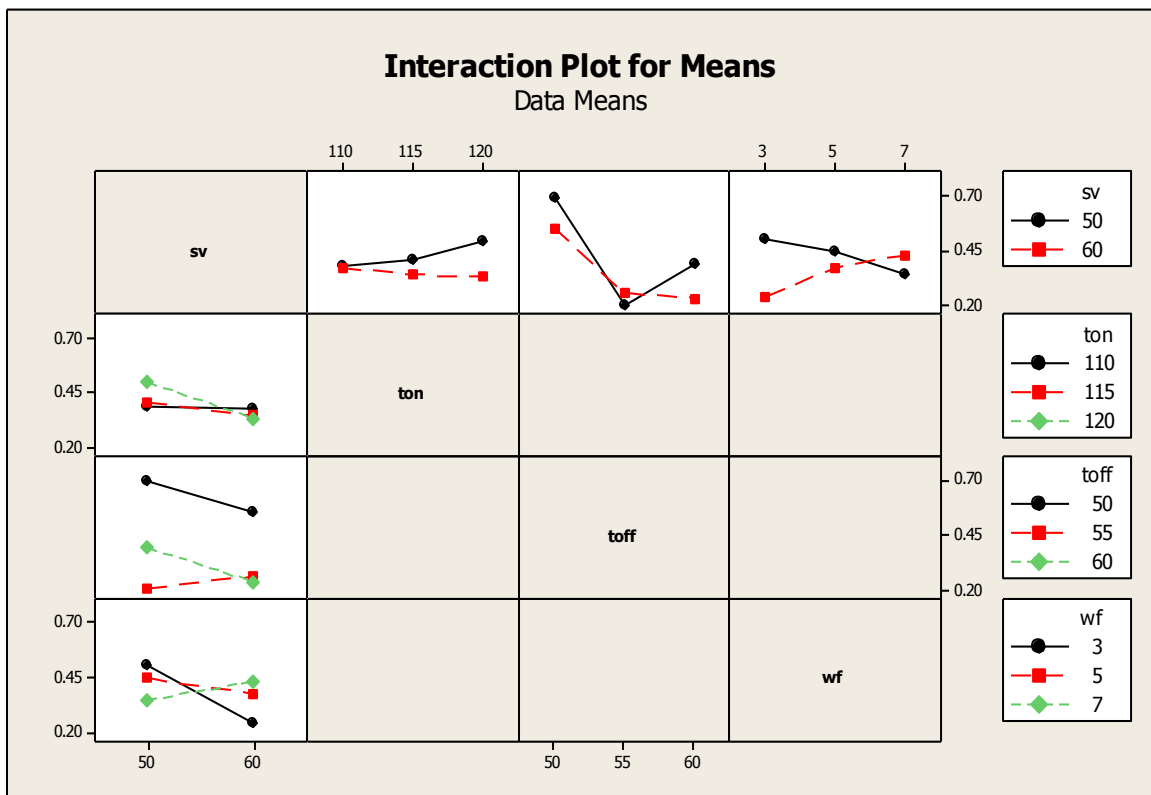


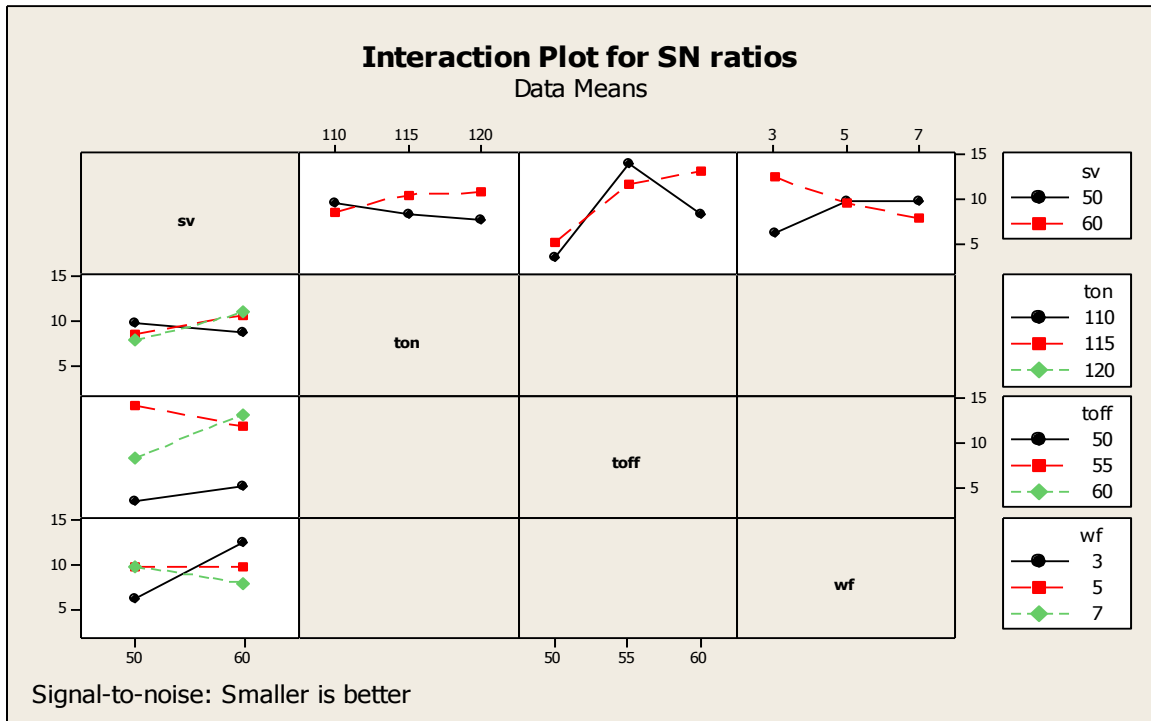
Figure 5.9 Effect of process parameters on percentage of dimensional deviation (Mean Data)



**Figure 5.10** Effect of process parameters on percentage of dimensional deviation (S/N Ratio)



**Figure 5.11** Effect of process parameter interactions on percentage of dimensional deviation (Mean Data)



**Figure 5.12** Effect of process parameter interactions on percentage of dimensional deviation (S/N Ratio)

The analysis of variance for mean data and S/N ratio has to be done as shown in table 5.9 and 5.10 respectively. Result shows that pulse off time is significant factor based on 95% level of confidence. The other process parameters and their interactions are not significant factors for % dimensional deviation.

**Table 5.9** Analysis of variance for percentage of dimensional deviation (Mean data)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SV	1	0.028800	0.028800	0.028800	2.91	0.163
T <sub>on</sub>	2	0.005953	0.005953	0.002976	0.30	0.756
T <sub>off</sub>	2	0.530453	0.461154	0.230577	23.30	0.006*
WF	2	0.004869	0.054004	0.027002	2.73	0.179
SV×T <sub>on</sub>	2	0.019308	0.019308	0.009654	0.98	0.452
SV×T <sub>off</sub>	2	0.092360	0.092360	0.046180	4.67	0.090
SV×WF	2	0.023760	0.023760	0.011880	1.20	0.391
Error	4	0.039592	0.039592	0.009898		
Total	17	0.745094				

\*Significant at 95 % Confidence Level

**Table 5.10** Analysis of variance for percentage of dimensional deviation (S/N Data)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SV	1	9.302	9.302	9.302	1.06	0.360
T <sub>on</sub>	2	0.300	0.300	0.150	0.02	0.983
T <sub>off</sub>	2	248.044	195.735	97.868	11.20	0.023*
WF	2	2.498	11.209	5.605	0.64	0.573
SV×T <sub>on</sub>	2	13.845	13.845	6.923	0.79	0.513
SV×T <sub>off</sub>	2	50.165	50.165	25.083	2.87	0.169
SV×WF	2	4.176	4.176	2.088	0.24	0.798
Error	4	34.947	34.947	8.737		
Total	17	363.277				

\*Significant at 95 % Confidence Level

The response table for mean data and S/N ratio are shown in table 5.11 and 5.12 respectively. The ranking for different process parameters has to be assigned based on delta value. Delta value shows that pulse off time is most relative important factor for percentage of dimensional deviation. The ranks show that pulse off time is greatly affected the percentage of dimensional deviation followed by spark gap set voltage, pulse on time and wire feed rate.

**Table 5.11** Response table for percentage of dimensional deviation (Mean Data)

Level	SV	T <sub>on</sub>	T <sub>off</sub>	WF
1	0.4294	0.3792	0.6275	0.3708
2	0.3494	0.3742	0.2292	0.4108
3		0.4150	0.3117	0.3867
Delta	0.0800	0.0408	0.3983	0.0400
Rank	2	3	1	4

**Table 5.12** Response table for percentage of dimensional deviation (S/N Ratio)

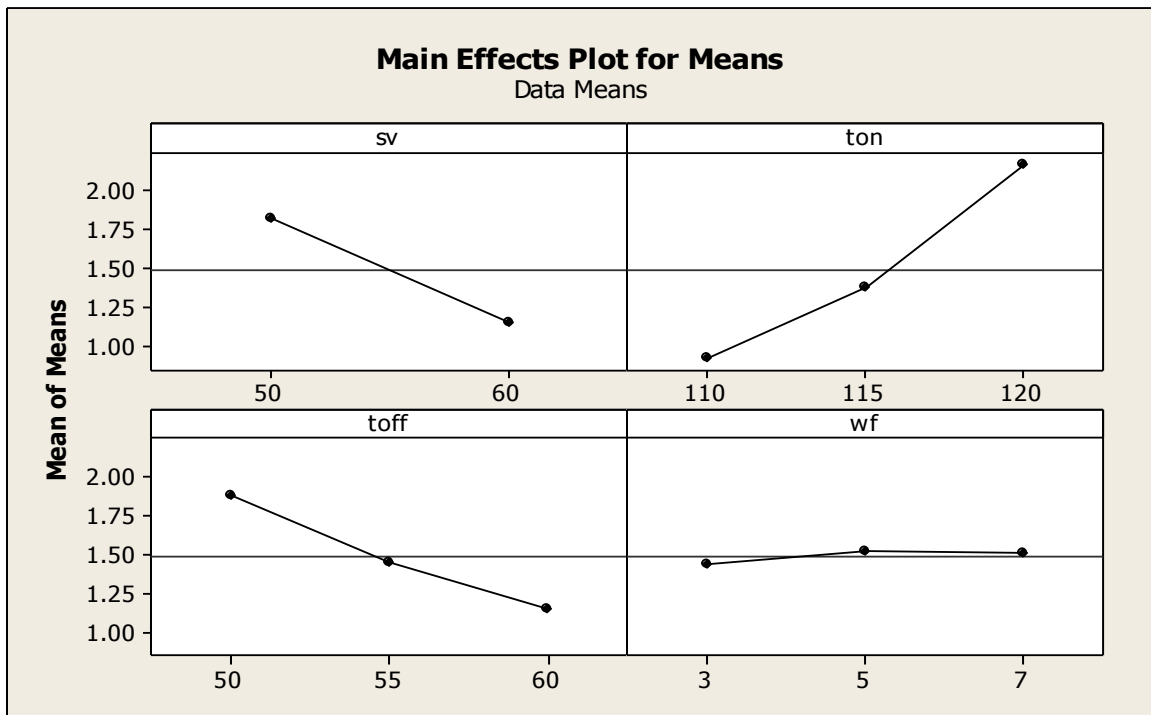
Level	SV	T <sub>on</sub>	T <sub>off</sub>	WF
1	8.620	9.173	4.256	9.400
2	10.058	9.487	13.018	9.762
3		9.356	10.742	8.855
Delta	1.438	0.315	8.762	0.906
Rank	2	3	1	4

## 5.2 Analysis and Discussion of Results for Deep Cryogenic treated die steel AISI D3

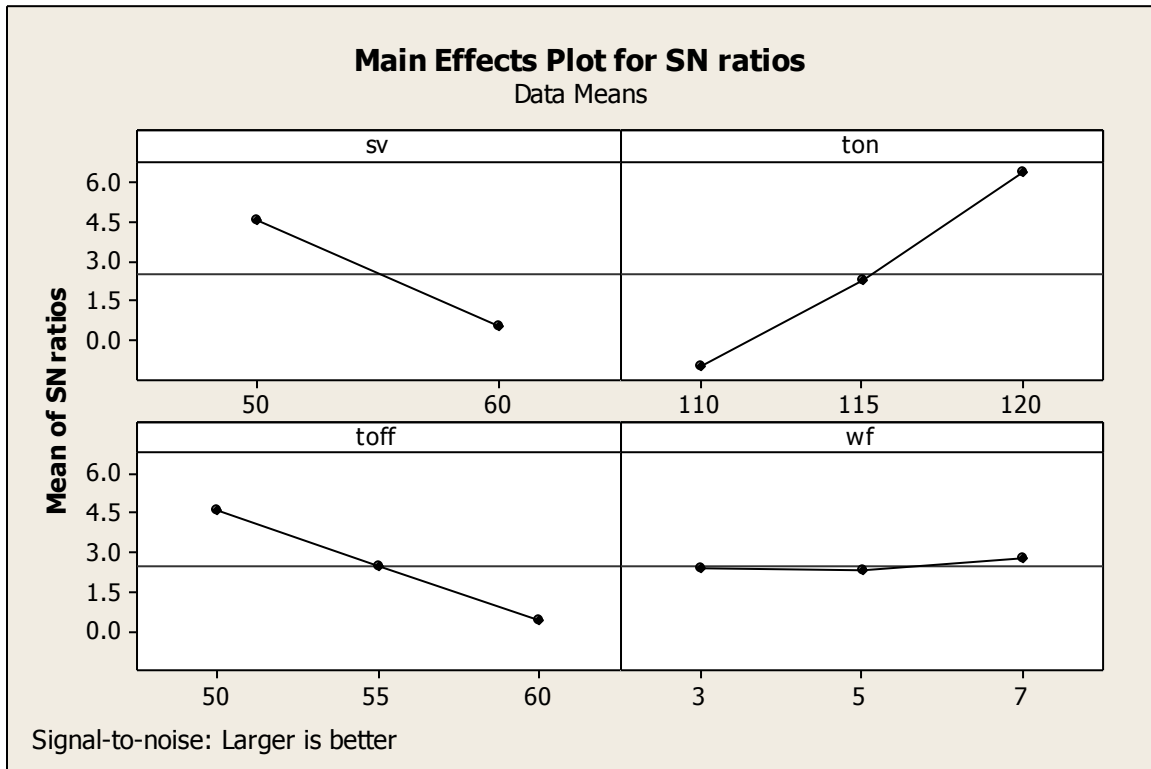
The analysis of results has to done based on mean data and S/N ratio to studies the effect of process parameters and their interactions on performance characteristics. The performance characteristics are material removal rate, surface roughness and percentage of dimensional deviation. The main effects for mean data and S/N ratio are drawn to study the effect of input parameters. The analysis of variance is studied to find out the significant factors. The response tables are also drawn to find out the rank and delta value of process parameters.

### 5.2.1 Effect on Material Removal Rate

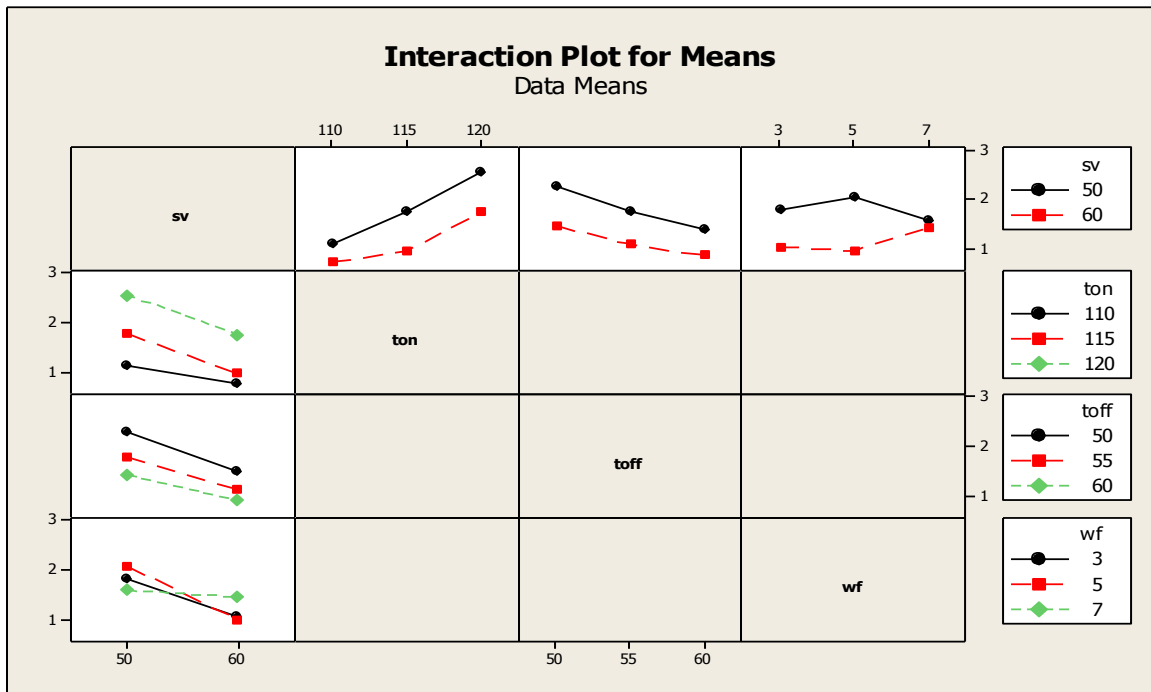
The experimental results for material removal rate are shown in table 4.15. The main effect plots are drawn for mean data and S/N ratio as shown in figure 5.13 and 5.14 respectively. Figure 5.13 shows the trend that material removal rate is decrease with increase in spark gap set voltage and pulse off time and increases with increase in pulse on time. The wire feed rate does not show clearly effect on material removal rate. The interactions plots for mean data and S/N ratio are drawn as shown in figure 5.15 and 5.16.



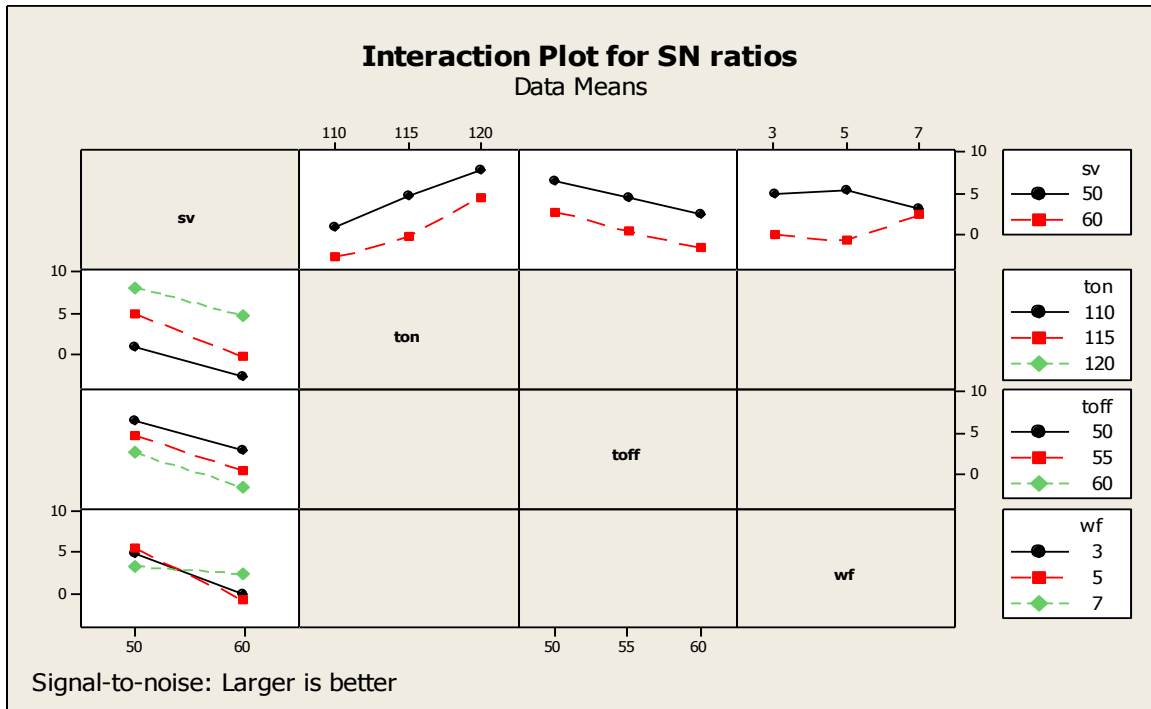
**Figure 5.13** Effect of process parameters on MRR (Mean Data)



**Figure 5.14** Effect of process parameters on MRR (S/N Ratio)



**Figure 5.15** Effect of process parameter interactions on MRR (Mean Data)



**Figure 5.16** Effect of process parameter interactions on MRR (S/N Ratio)

The analysis of variance for mean data and S/N ratio are shown in table 5.13 and 5.14. Analysis of variance for mean data shows that spark gap set voltage, pulse on time and pulse off time are significant factors at 95% level of confidence. Table 5.14 shows that spark gap set voltage, pulse on time and pulse off time are significant factors that affect the material removal rate. The interactions of spark gap set voltage and pulse on time, spark gap set voltage and wire feed rate are also significant as shown in table 5.14.

**Table 5.13** Analysis of variance for MRR (Mean data)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SV	1	1.99567	1.99567	1.99567	64.72	0.001*
T <sub>on</sub>	2	4.74174	4.74174	2.37087	76.88	0.001*
T <sub>off</sub>	2	1.61518	1.13438	0.56719	18.39	0.010*
WF	2	0.02986	0.08429	0.04214	1.37	0.353
SV×T <sub>on</sub>	2	0.20622	0.20622	0.10311	3.34	0.140
SV×T <sub>off</sub>	2	0.10474	0.10474	0.05237	1.70	0.292
SV×WF	2	0.20134	0.20134	0.10067	3.26	0.144
Error	4	0.12335	0.12335	0.03084		
Total	17	9.01809				

\*Significant at 95 % Confidence Level

**Table 5.14** Analysis of variance for MRR (S/N Ratio)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SV	1	75.014	75.014	75.014	429.89	0.000*
T <sub>on</sub>	2	163.610	163.610	81.805	468.81	0.000*
T <sub>off</sub>	2	53.290	31.283	15.642	89.64	0.000*
WF	2	0.796	0.684	0.342	1.96	0.255
SV×T <sub>on</sub>	2	2.814	2.814	1.407	8.06	0.039*
SV×T <sub>off</sub>	2	0.245	0.245	0.123	0.70	0.548
SV×WF	2	2.475	2.475	1.237	7.09	0.048*
Error	4	0.698	0.698	0.174		
Total	17	298.943				

\*Significant at 95 % Confidence Level

The response table of material removal rate for mean data and S/N ratio are shown in table 5.15 and 5.16 respectively. Based on these tables it has been found that pulse on time is most relative important factor for material removal rate. The ranking shows that pulse on time is most relative important factor towards material removal rate followed by pulse off time, spark gap set voltage and wire feed rate.

**Table 5.15** Response table for MRR (Mean Data)

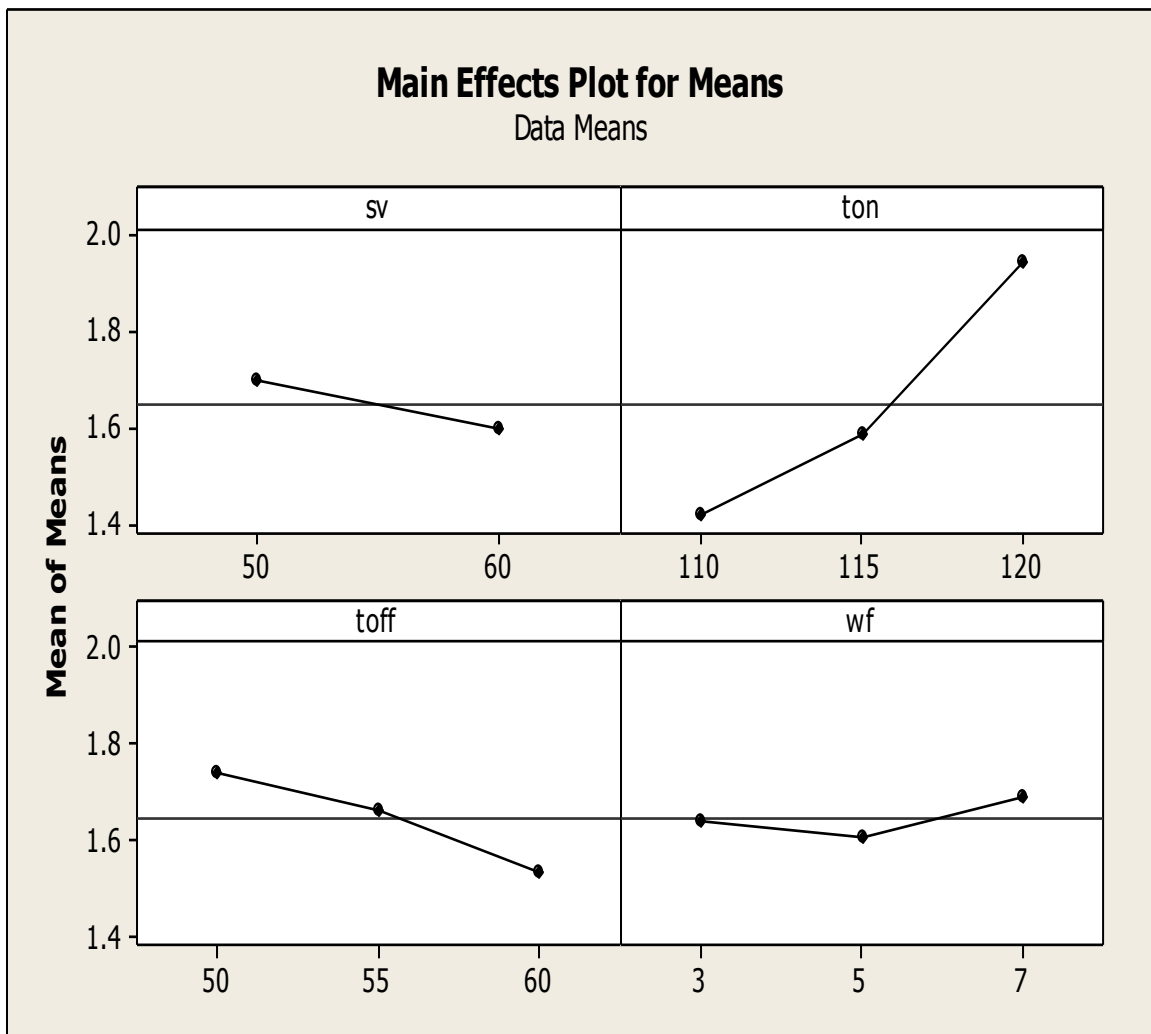
Level	SV	T <sub>on</sub>	T <sub>off</sub>	WF
1	1.8235	0.9285	1.8775	1.4337
2	1.1576	1.3738	1.4463	1.5269
3		2.1693	1.478	1.5110
Delta	0.6659	1.2408	0.7298	0.0933
Rank	3	1	2	4

**Table 5.16** Response table for MRR (S/N Ratio)

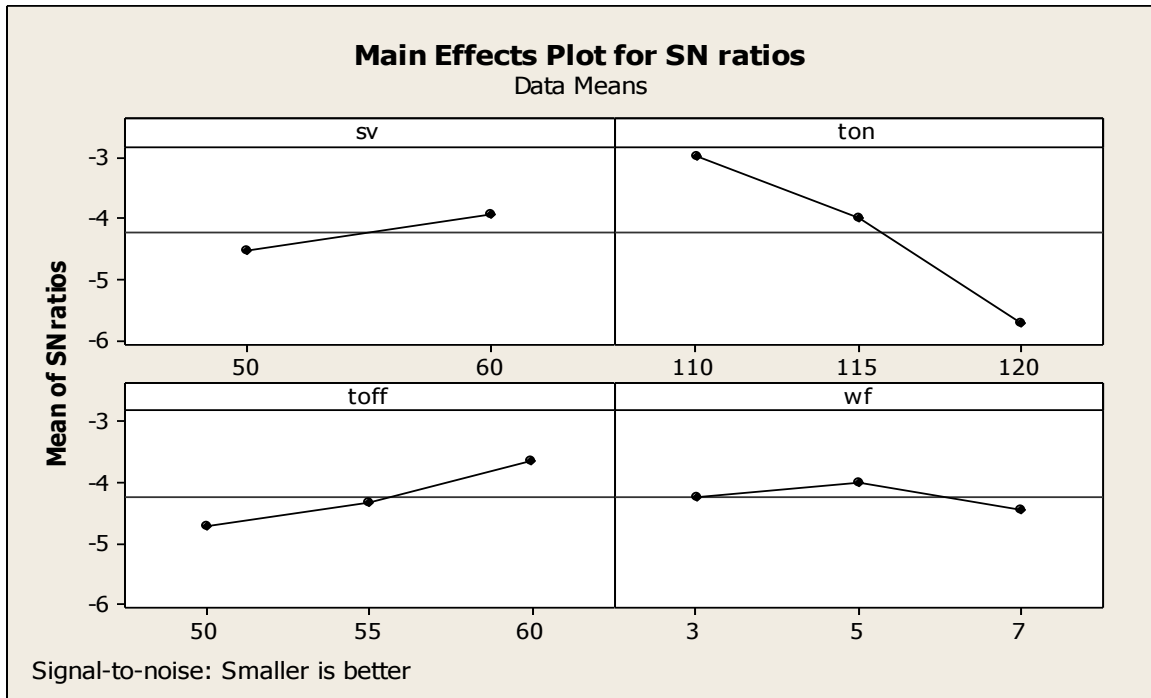
Level	SV	T <sub>on</sub>	T <sub>off</sub>	WF
1	4.5633	-1.0293	4.6429	2.4123
2	0.4804	2.2538	2.4940	2.3371
3		6.3410	0.4285	2.8161
Delta	4.0829	7.3703	4.2144	0.4789
Rank	3	1	2	4

### 5.2.2 Effect on Surface Roughness

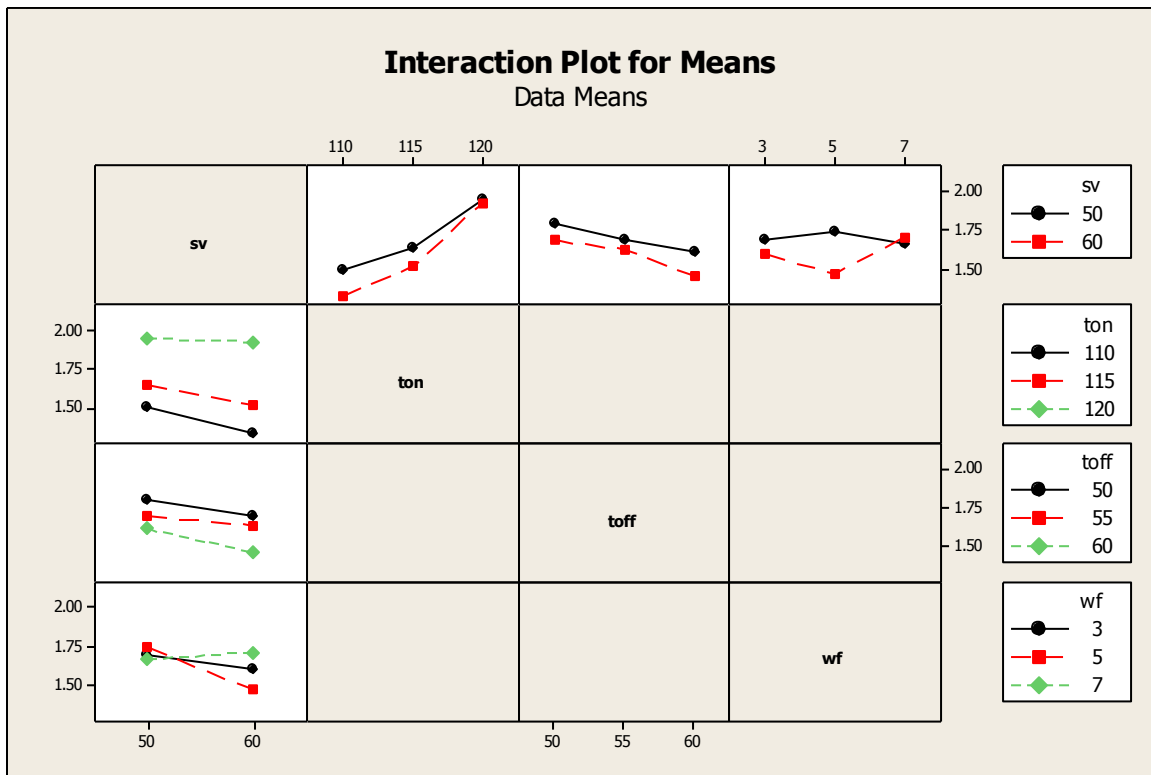
The experimental results of performed experiments are shown in table 4.16. With these results the mean effect plots for mean data and S/N ratio are drawn as shown in figure 5.17 and 5.18 respectively. Figure 5.17 shows the trend that surface roughness is decreases with increase in spark gap set voltage and pulse off time. It increases with increase in pulse on time and it first decrease and then slightly increases with increase in wire feed rate. The interaction plots for mean data and S/N ratio are shown in figure 5.19 and 5.20 respectively. Due to increase in pulse on time the large amount of discharge energy produced craters on the machining surface so surface roughness is increased.



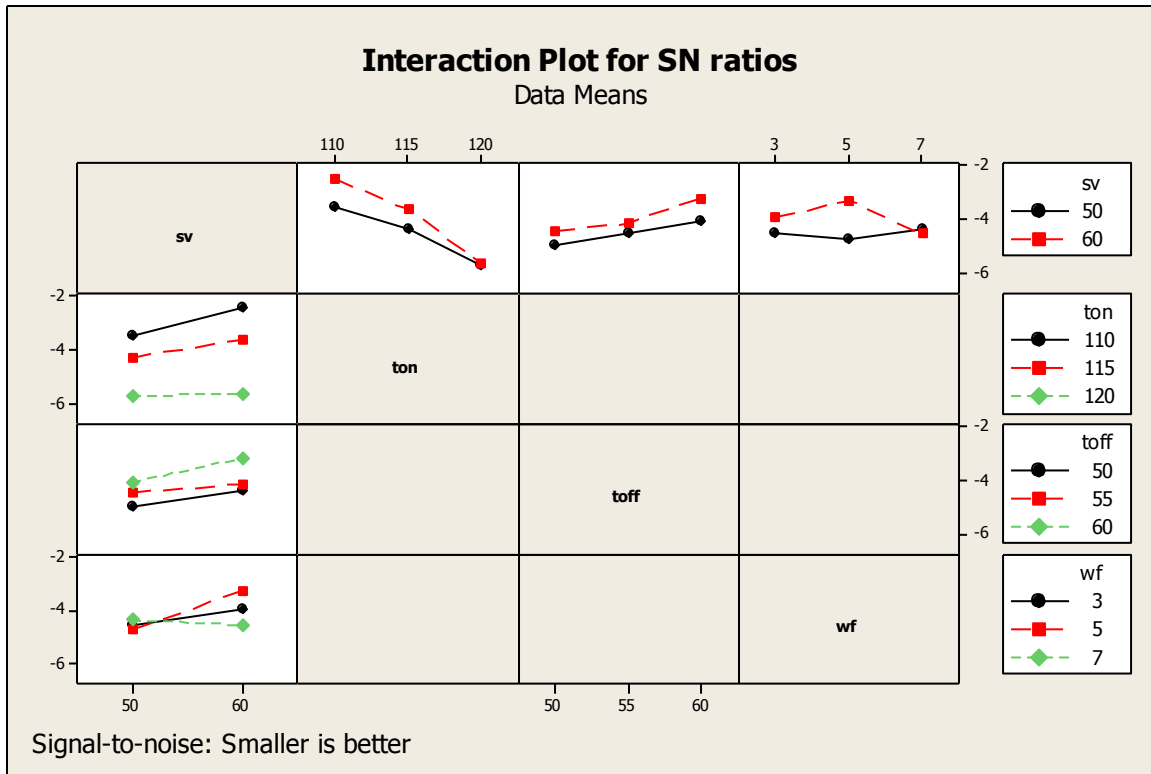
**Figure 5.17** Effect of process parameters on Surface Roughness (Mean Data)



**Figure 5.18** Effect of process parameters on Surface Roughness (S/N Ratio)



**Figure 5.19** Effect of process parameter interactions on Surface Roughness (Mean Data)



**Figure 5.20** Effect of process parameter interactions on Surface Roughness (S/N Ratio)

The analysis of variance is carried out for mean data and S/N ratio as shown in table 5.17 and 5.18. Table 5.17 shows that the process parameters spark gap set voltage, pulse on time and pulse off time are significant based on 95% level of confidence. Analysis of variance for S/N ratio shows that all the process parameters are significant. The interactions of spark gap set voltage and pulse on time, spark gap set voltage and wire feed rate are significant as shown in table 5.18.

**Table 5.17** Analysis of variance for Surface Roughness (Mean data)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SV	1	0.049089	0.049089	0.049089	18.21	0.013*
T <sub>on</sub>	2	0.858786	0.858786	0.429393	159.28	0.000*
T <sub>off</sub>	2	0.131586	0.079756	0.039878	14.79	0.014*
WF	2	0.020536	0.017272	0.008636	3.20	0.148
SV×T <sub>on</sub>	2	0.016336	0.016336	0.008168	3.03	0.158
SV×T <sub>off</sub>	2	0.003272	0.003272	0.001636	0.61	0.589
SV×WF	2	0.024539	0.024539	0.012269	4.55	0.093
Error	4	0.010783	0.010783	0.002696		
Total	17	1.114928				

\*Significant at 95 % Confidence Level

**Table 5.18** Analysis of variance for Surface Roughness (S/N Ratio)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SV	1	1.6938	1.6938	1.6938	105.63	0.001*
T <sub>on</sub>	2	23.0115	23.0115	11.5057	717.52	0.000*
T <sub>off</sub>	2	3.4918	1.9828	0.9914	61.83	0.001*
WF	2	0.6261	0.4421	0.2211	13.79	0.016*
SV×T <sub>on</sub>	2	0.6326	0.6326	0.3163	19.73	0.008*
SV×T <sub>off</sub>	2	0.0505	0.0505	0.0253	1.58	0.313
SV×WF	2	0.5254	0.5254	0.2627	16.38	0.012*
Error	4	0.0641	0.0641	0.0160		
Total	17	30.0960				

\*Significant at 95 % Confidence Level

The response tables for mean data and S/N ratio are shown in table 5.19 and 5.20 respectively. The delta value shows that pulse on time is most relative important factor towards the surface roughness. The ranking of different process parameters shows that pulse on time is mostly relative important factor followed by pulse off time, spark gap set voltage and wire feed rate.

**Table 5.19** Response table for Surface Roughness (Mean Data)

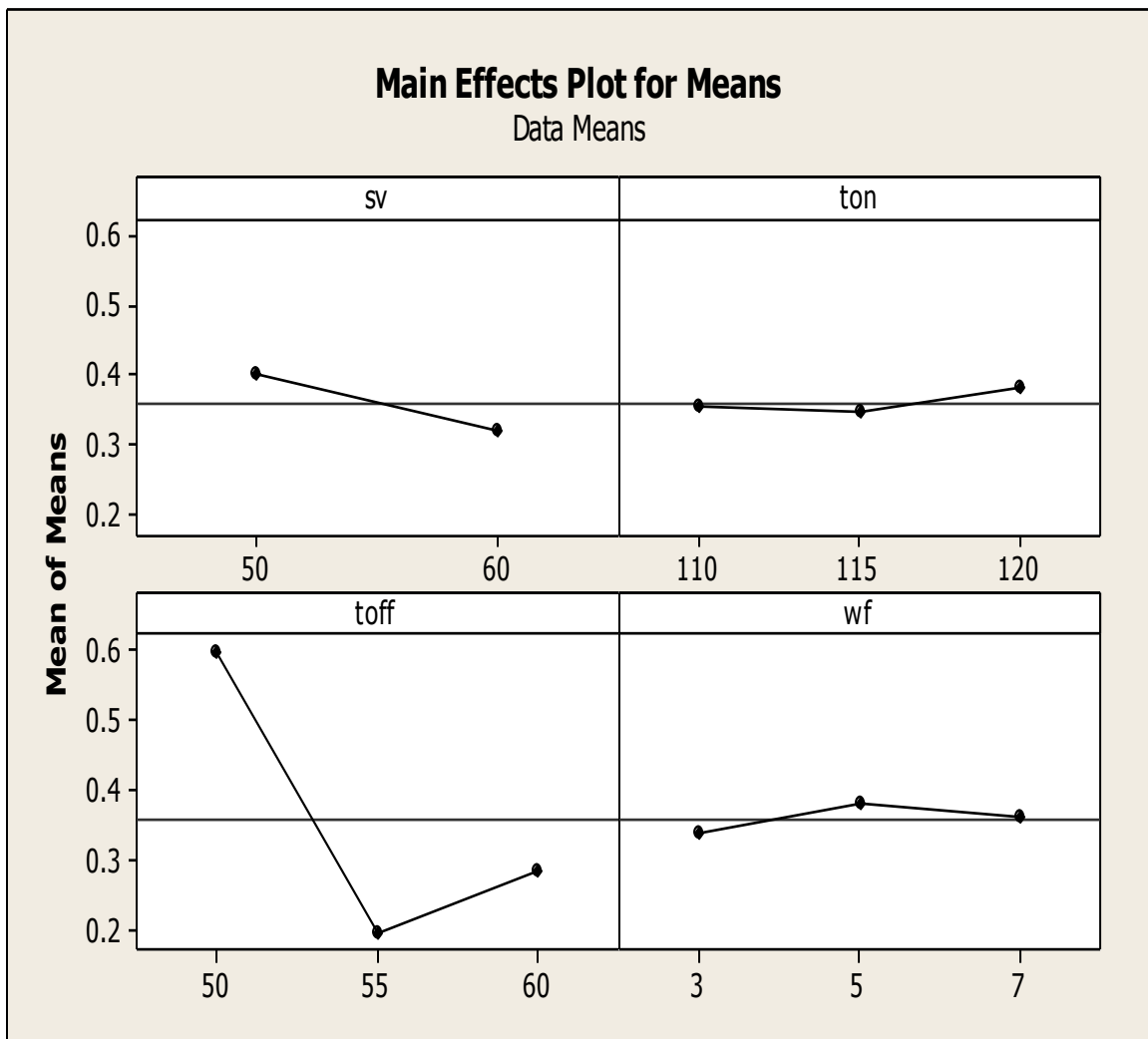
Level	SV	T <sub>on</sub>	T <sub>off</sub>	WF
1	1.698	1.415	1.742	1.643
2	1.594	1.584	1.662	1.607
3		1.939	1.534	1.689
Delta	0.104	0.524	0.207	0.083
Rank	3	1	2	4

**Table 5.20** Response table for Surface Roughness (S/N Ratio)

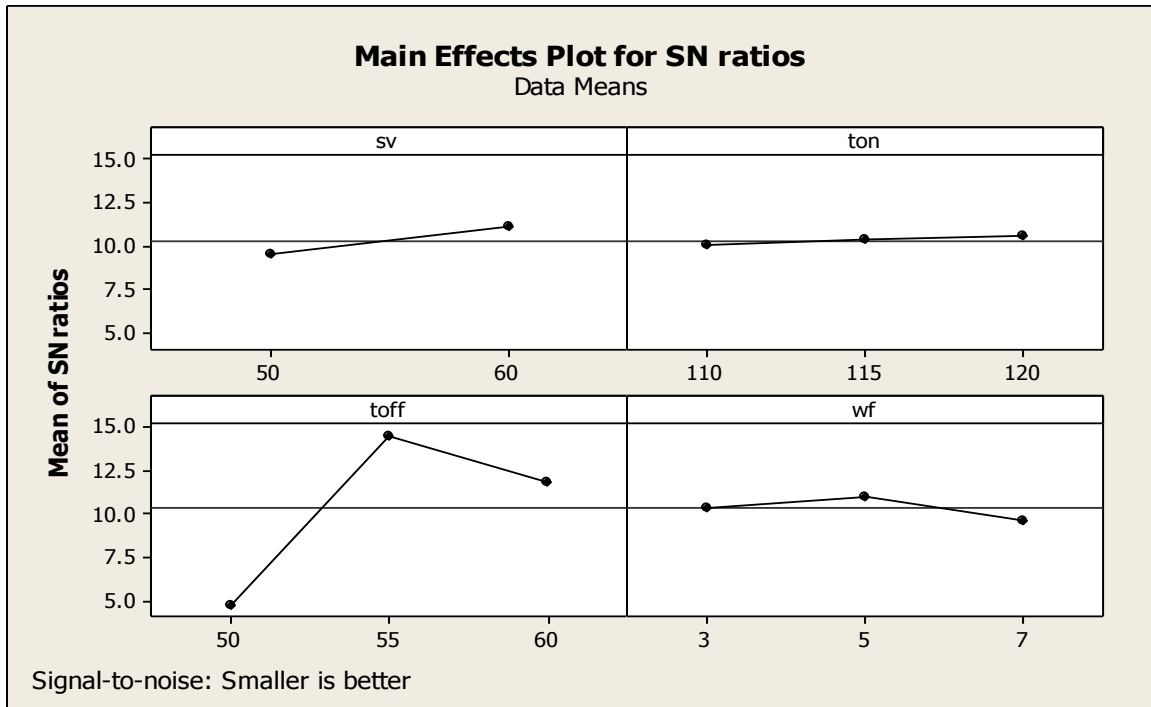
Level	SV	T <sub>on</sub>	T <sub>off</sub>	WF
1	-4.539	-2.987	-4.717	-4.243
2	-3.925	-3.985	-4.335	-3.999
3		-5.724	-3.649	-4.455
Delta	0.614	2.736	1.064	0.456
Rank	3	1	2	4

### 5.2.3 Effect on Percentage of Dimensional deviation

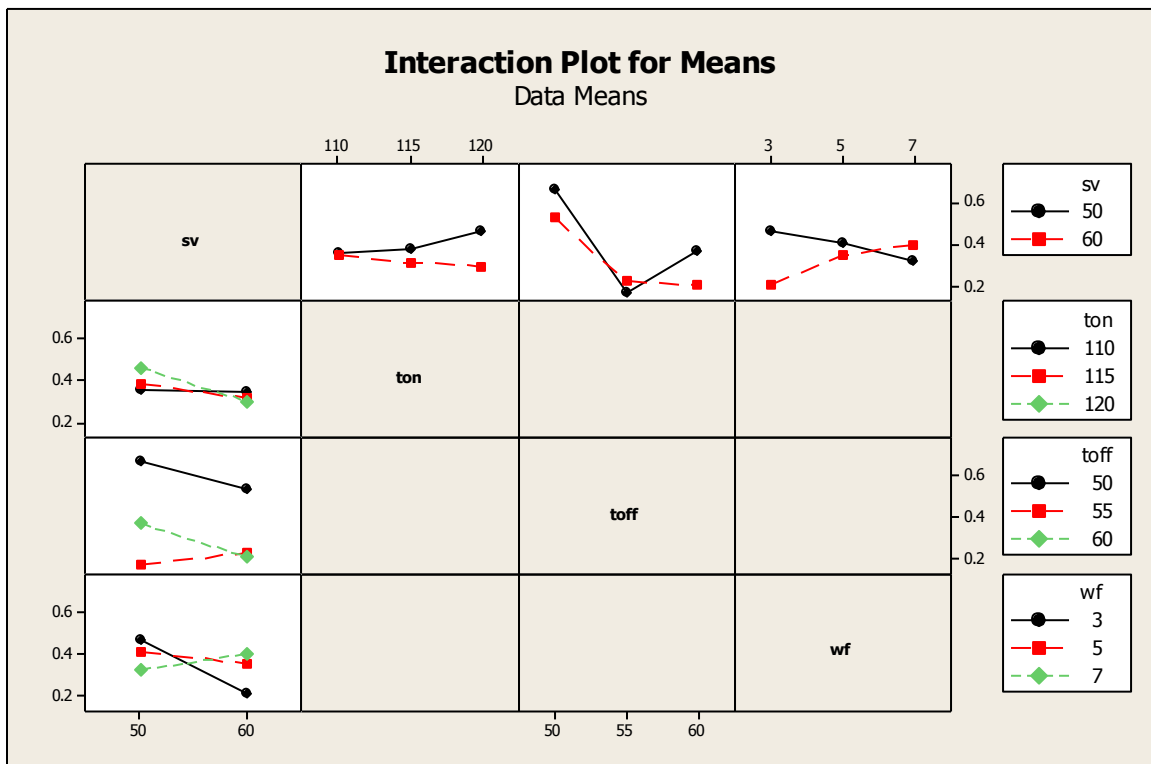
The results of performed experiments for percentage of dimensional deviation are shown in table 4.17. Based on these results the main effect plots for mean data and S/N ratio are shown in figure 5.21 and 5.22 respectively. Figure 5.21 shows the trend that percentage of dimensional deviation is decreases with increase in spark gap set voltage. With increase in pulse off time first decrease and then slightly increases. When pulse on time is increased then percentage of dimensional deviation firstly decreases then slightly increases and for wire feed rate clearly effect is not shown. The interactions plots of process parameters for mean data and S/N ratio are shown in figure 5.23 and 5.24 respectively.



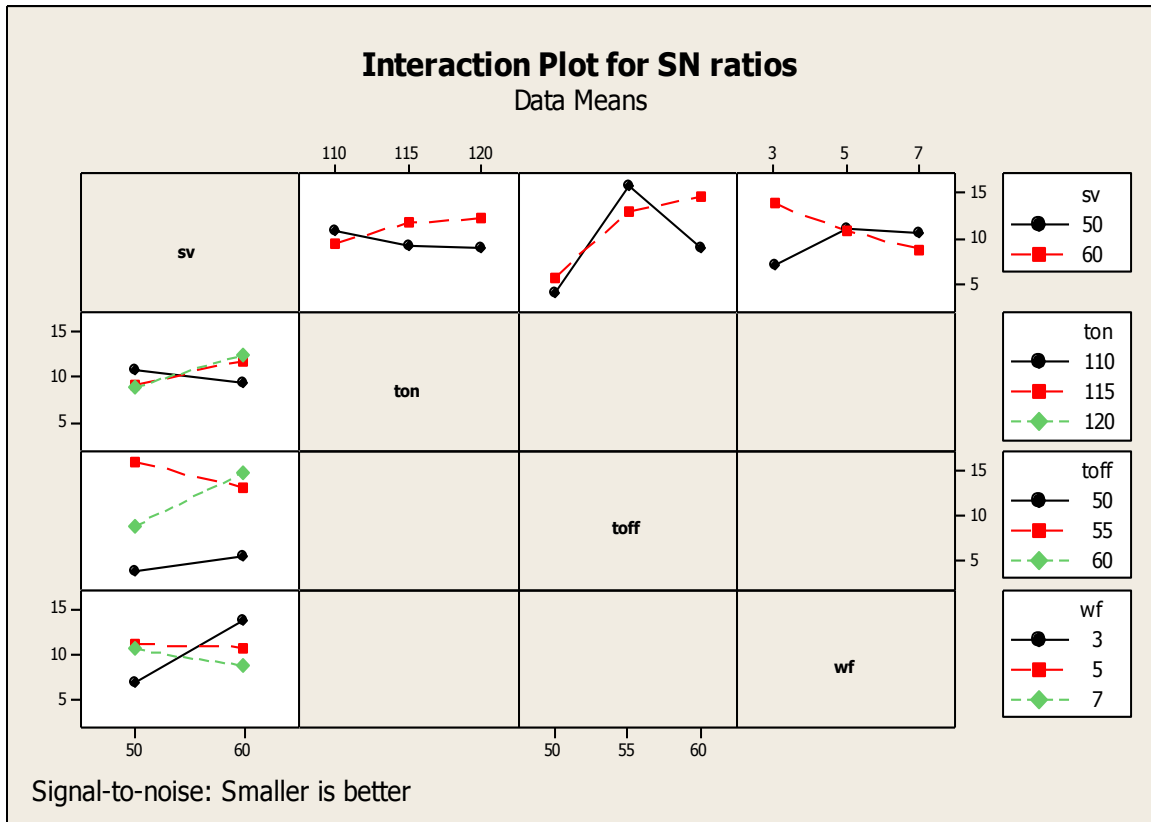
**Figure 5.21** Effect of process parameters on percentage of dimensional deviation (Mean Data)



**Figure 5.22** Effect of process parameters on percentage of dimensional deviation (S/N Ratio)



**Figure 5.23** Effect of process parameter interactions on percentage of dimensional deviation (Mean Data)



**Figure 5.24** Effect of process parameter interactions on percentage of dimensional deviation (S/N Ratio)

The analysis of variance has to be done for mean data and S/N ratio as shown in table 5.21 and 5.22 respectively. Table 5.21 and 5.22 shows that pulse off time is only significant factor at 95% level of confidence.

**Table 5.21** Analysis of variance for percentage of dimensional deviation (Mean data)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SV	1	0.02920	0.02920	0.02920	2.80	0.169
T <sub>on</sub>	2	0.00348	0.00348	0.00174	0.17	0.852
T <sub>off</sub>	2	0.53627	0.47550	0.23775	22.81	0.006*
WF	2	0.00542	0.05663	0.02831	2.72	0.180
SV×T <sub>on</sub>	2	0.01874	0.01874	0.00937	0.90	0.476
SV×T <sub>off</sub>	2	0.09514	0.09514	0.04757	4.57	0.093
SV×WF	2	0.02673	0.02673	0.01337	1.28	0.371
Error	4	0.04168	0.04168	0.01042		
Total	17	0.75667				

\*Significant at 95 % Confidence Level

**Table 5.22** Analysis of variance for percentage of dimensional deviation (S/N Ratio)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
SV	1	11.30	11.30	11.30	0.87	0.405
T <sub>on</sub>	2	0.72	0.72	0.36	0.03	0.973
T <sub>off</sub>	2	308.15	248.48	124.24	9.53	0.030*
WF	2	5.28	12.69	6.34	0.49	0.647
SV×T <sub>on</sub>	2	20.43	20.43	10.21	0.78	0.516
SV×T <sub>off</sub>	2	66.81	66.81	33.41	2.56	0.192
SV×WF	2	6.91	6.91	3.45	0.26	0.780
Error	4	52.15	52.15	13.04		
Total	17	471.75				
*Significant at 95 % Confidence Level						

The response tables for mean data and S/N ratio are shown in table 5.23 and 5.24 respectively. Result shows that pulse off time is most relative important factor towards the percentage of dimensional deviation. Ranking of different process parameters based on delta value shows that pulse off time is mostly relative important followed by spark gap set voltage, wire feed rate and pulse on time.

**Table 5.23** Response table for Percentage of dimensional deviation (Mean Data)

Level	SV	T <sub>on</sub>	T <sub>off</sub>	WF
1	0.4000	0.3525	0.5983	0.3383
2	0.3194	0.3475	0.1958	0.3808
3		0.3792	0.2850	0.3600
Delta	0.0806	0.0317	0.4025	0.0425
Rank	2	4	1	3

**Table 5.24** Response table for Percentage of dimensional deviation (S/N Ratio)

Level	SV	T <sub>on</sub>	T <sub>off</sub>	WF
1	9.529	10.063	4.682	10.366
2	11.114	10.350	14.492	10.962
3		10.552	11.791	9.637
Delta	1.585	0.489	9.810	1.324
Rank	2	4	1	3

# Chapter 6

## Comparisons between Machining of Deep Cryogenically treated and Non treated Workpiece

### 6.1 Comparison of Performance Characteristics

The performance characteristics are material removal rate, surface roughness and percentage of dimensional deviation. After performing the experiments the results of deep cryogenic treated workpiece are compared with non treated workpiece. The bar graphs are plotted for study the comparison of performance characteristics.

#### 6.1.1 Comparison of Material Removal Rate

The experimental results of material removal rate are plotted on bar graph as shown in figure 6.1. With deep cryogenic treatment material removal rate is increased due to increase in electrical conductivity of workpiece [23]. After machining of deep cryogenic treated workpiece the material removal rate is increased is upto 21.27% based on mean data.

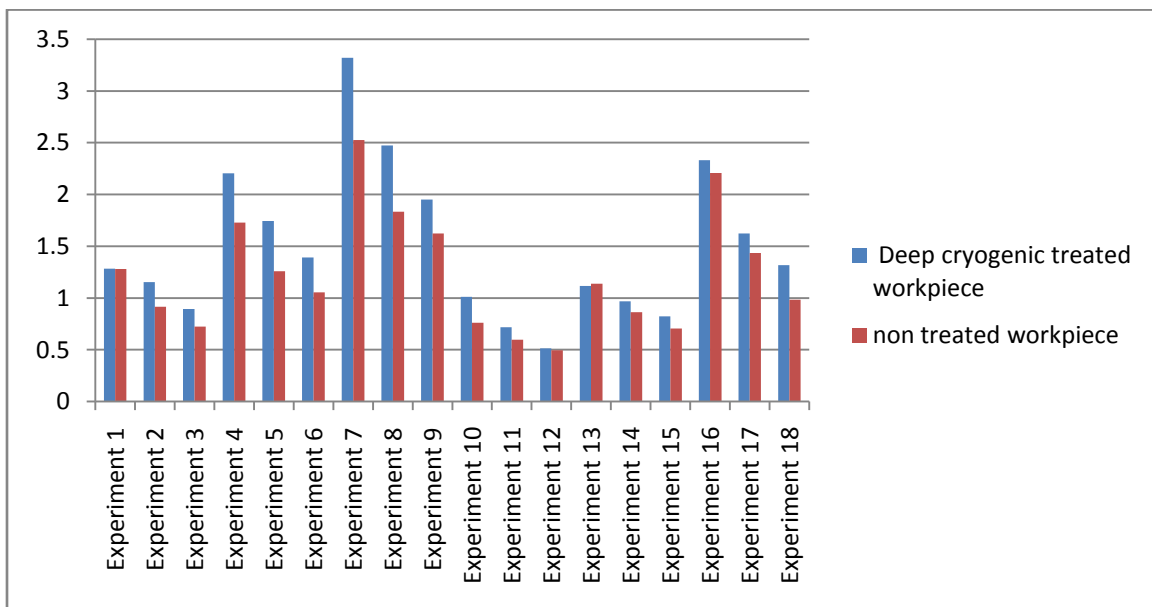


Figure 6.1 Bar graph for comparison of MRR

### 6.1.2 Comparison of Surface Roughness

The experimental results of surface roughness are plotted on bar graph for comparison of cryogenic treatment as shown in figure 6.2. The bar graph shows that surface roughness is increases with deep cryogenic treatment. With deep cryogenic treatment the surface roughness is increased upto 34% based on mean data. The surface roughness is increased due to increase in discharge energy during machining.

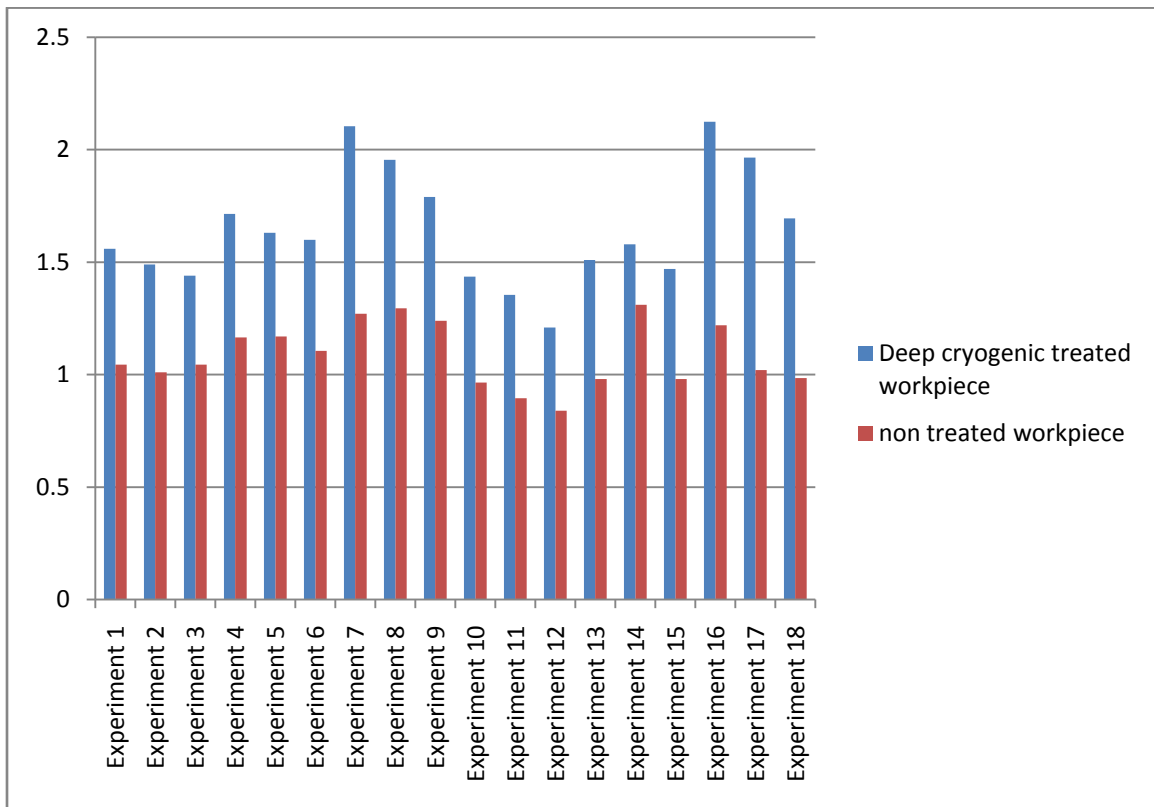


Figure 6.2 Bar graph for comparison of Surface Roughness

### 6.1.3 Comparison for percentage of dimensional deviation

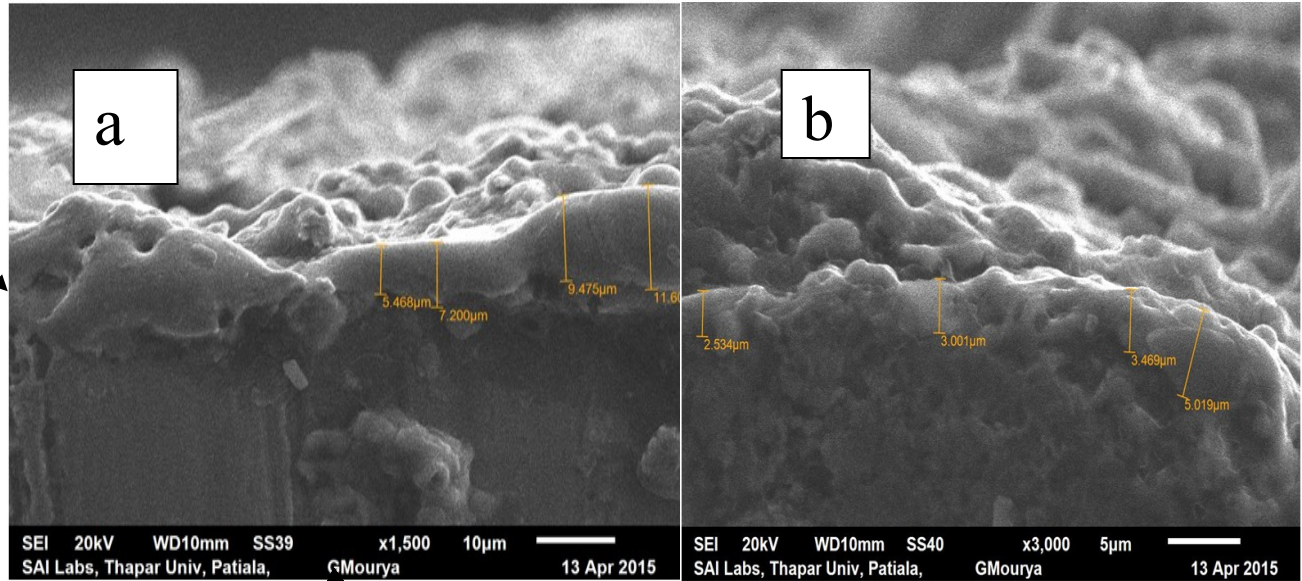
The results of each experiment for percentage of dimensional deviation are plotted on bar for comparison of deep cryogenic treatment. Figure 6.3 shows that percentage of dimensional deviation is decreases with deep cryogenic treatment. The decrease in percentage of dimensional deviation is 7.62% based on mean data after deep cryogenic treatment. This shows that with deep cryogenic treatment the stability of wire EDM increases during machining.



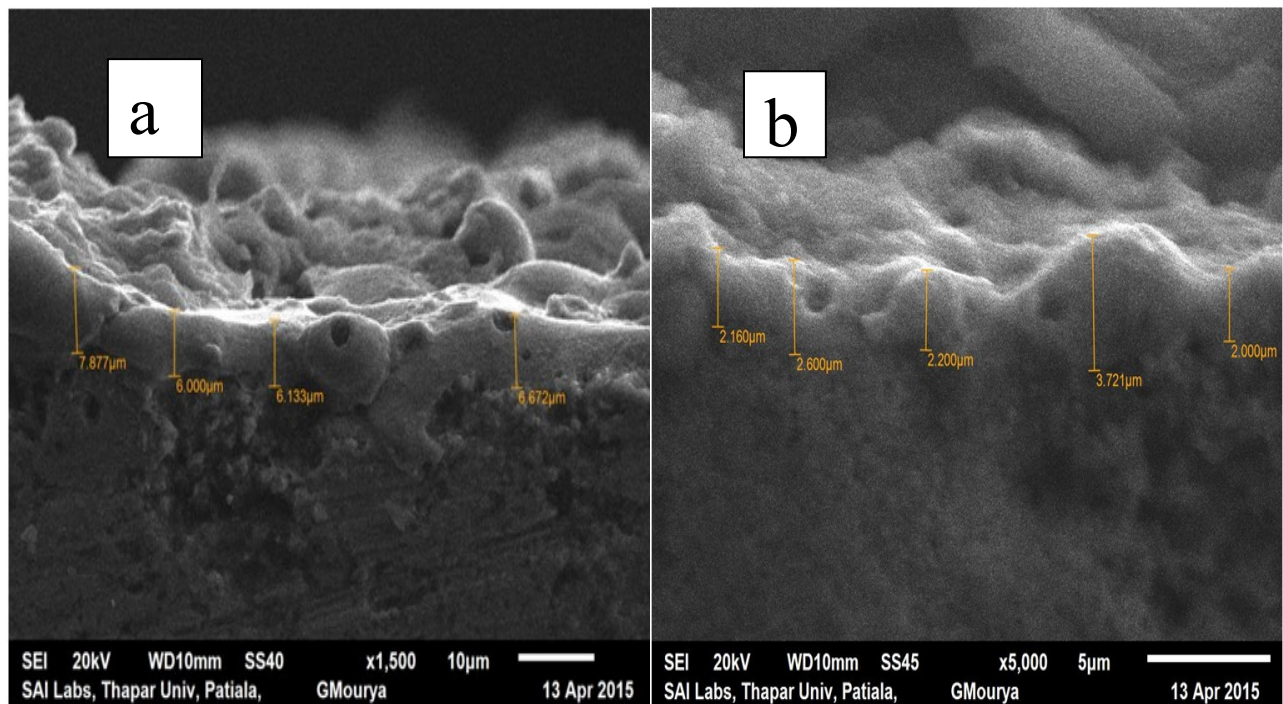
**Figure 6.3** Bar graph for comparison of percentage of dimensional deviation

## 6.2 Comparison of SEM for deep cryogenic treated workpiece and non treated workpiece

Recast layer can be measured by using scanning electron microscope at different levels of magnification. The recast layer is defined as the white layer produced by electric discharge during machining, the electric discharge can melt the metal and it resolidified on machining surface without flushed out by dielectric medium. The scanning electron microscopy of selected WEDM samples of experiment no. 7, 8 and 12 has to be done for deep cryogenic treated workpiece and non treated workpiece. Figure 6.4 shows the SEM micrographs of recast layer for both treated and non treated workpiece. The average recast layer thickness of deep cryogenic treated workpiece and non treated workpiece for experiment no. 7 are 8.43  $\mu\text{m}$  and 3.50  $\mu\text{m}$  respectively. Result shows that average recast layer thickness are increased with deep cryogenic treatment due to increase in conductivity of workpiece after treatment.

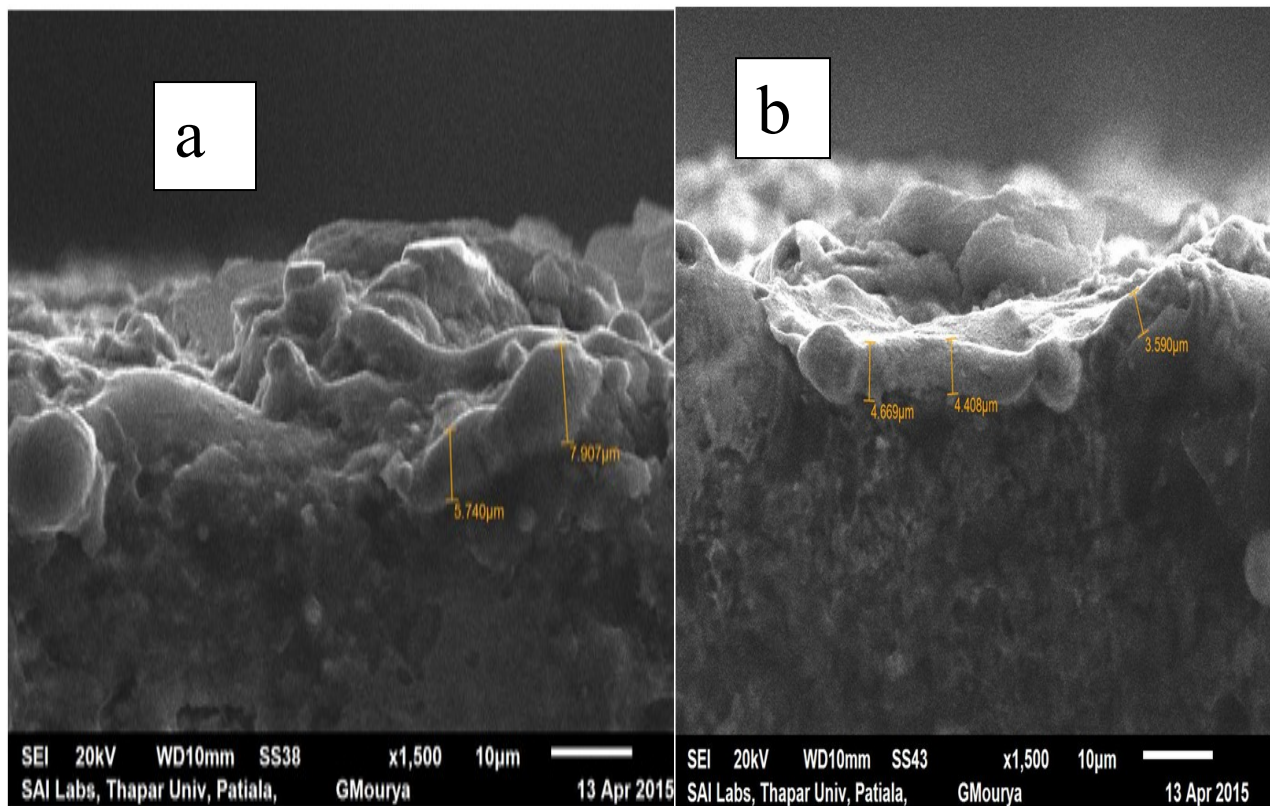


**Figure 6.4** SEM micrographs for recast layer of WEDM samples at  $T_{on}= 120$  units,  $T_{off}= 50$  units,  $SV= 50$  volts and  $WF= 5$  m/min (a) For deep cryogenic treated workpiece (b) For non treated workpiece



**Figure 6.5** SEM micrographs for recast layer of WEDM samples at  $T_{on}= 120$  units,  $T_{off}= 55$  units,  $SV= 50$  volts and  $WF= 7$  m/min (a) For deep cryogenic treated workpiece (b) For non treated workpiece

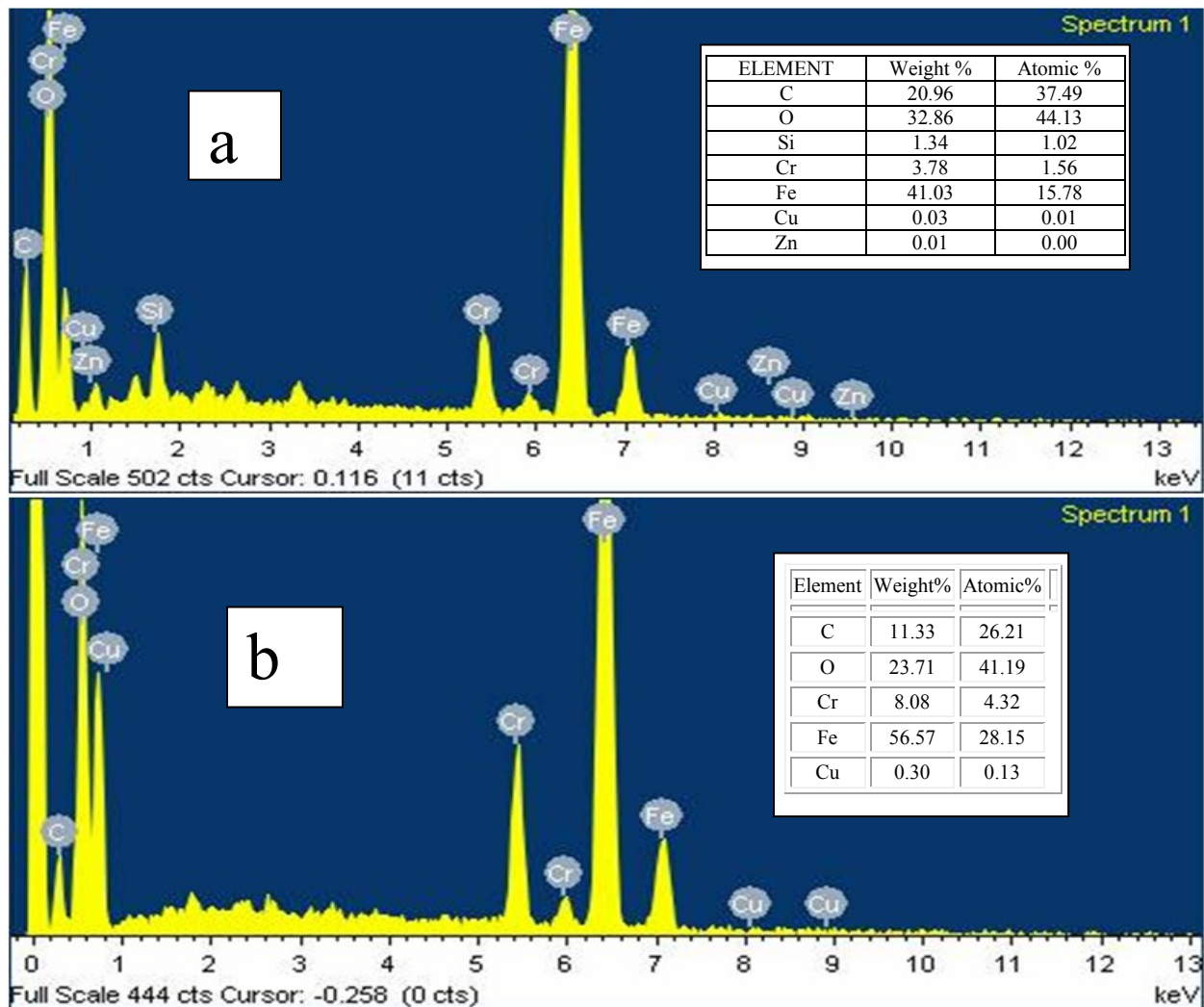
Figure 6.5 shows the average recast layer thickness of WEDM samples of experiment no. 8 for deep cryogenic treatment and non treatment workpiece. The average recast layer thicknesses for deep cryogenic treated and non treated workpiece are 6.67  $\mu\text{m}$  and 2.53  $\mu\text{m}$  respectively. Similarly figure 6.6 shows the average recast layer thickness of WEDM samples for experiment no. 12, the average recast layer thickness for cryogenic treated and non treated workpiece are 6.82  $\mu\text{m}$  and 4.22  $\mu\text{m}$  respectively. Result shows that average recast layer thickness is increased with increase in pulse on time and decreased with increase in pulse off time and spark gap set voltage as shown in figure 6.4 to 6.6. The average recast layer thickness is 26.38 % decreased with increase in pulse off time from 50 units to 55 units for deep cryogenic treatment and for non treated workpiece decrease in average recast layer thickness is 38.33 %. Result shows that pulse on time, pulse off time and spark gap set voltage has significantly effect on the average recast layer thickness of WEDM samples.



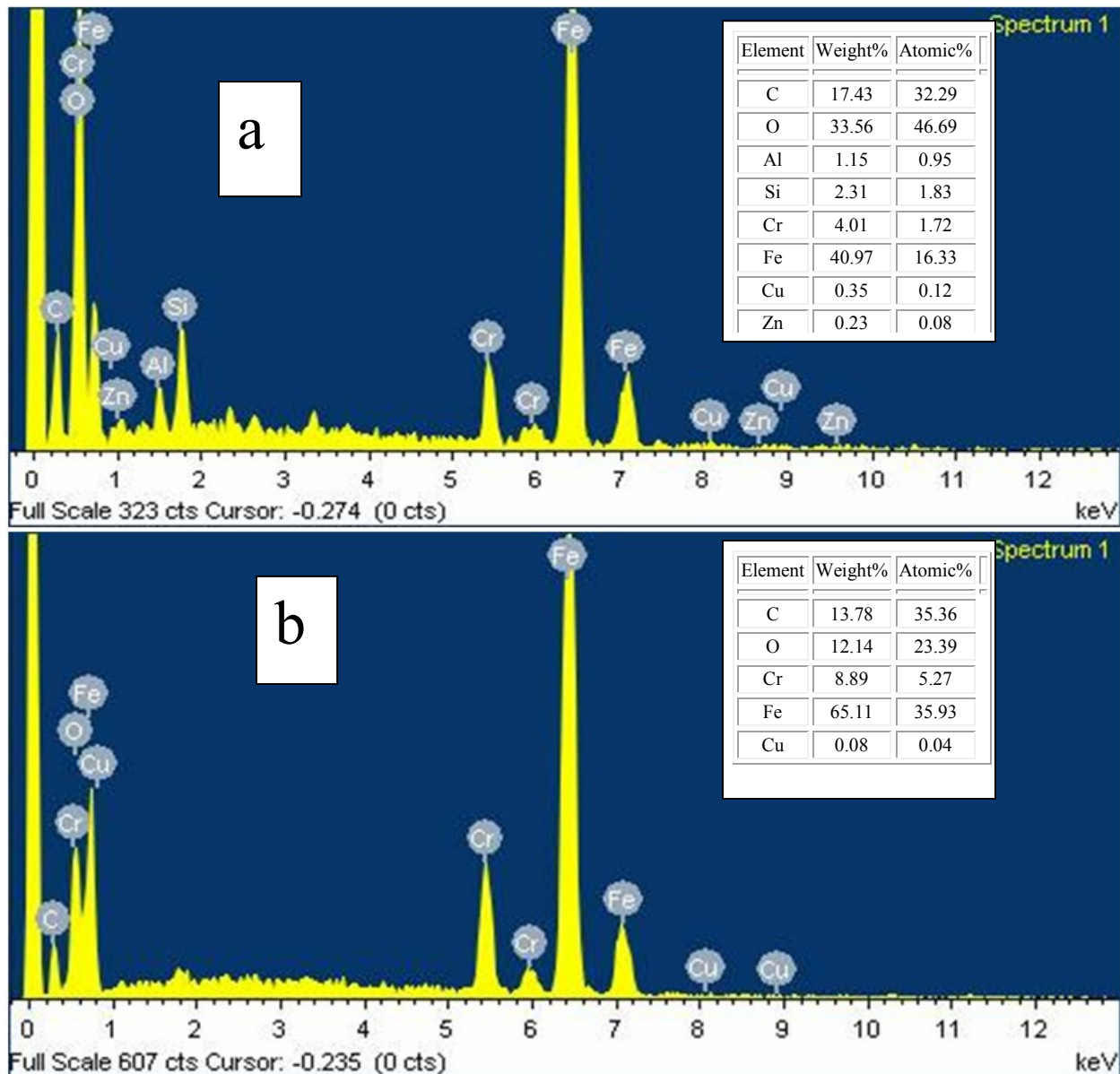
**Figure 6.6** SEM micrographs for recast layer of WEDM samples at  $T_{on}= 110$  units,  $T_{off}= 60$  units,  $SV= 60$  volts and  $WF= 5$  m/min (a) For deep cryogenic treated workpiece (b) For non treated workpiece

### 6.3 Comparison of EDS for deep cryogenic treated workpiece and non treated workpiece

Energy dispersive spectroscopy used to check the accumulation of different elements on the WEDM machined surface. EDS results shows that some elements of brass wire are found on machined surface of WEDM samples. The elements of brass wire are copper and zinc is struck on machined surface during sparking due to melting and resolidification on machined surface. Figure 6.7 shows the EDS analysis of deep cryogenic treated and non treated WEDM samples.

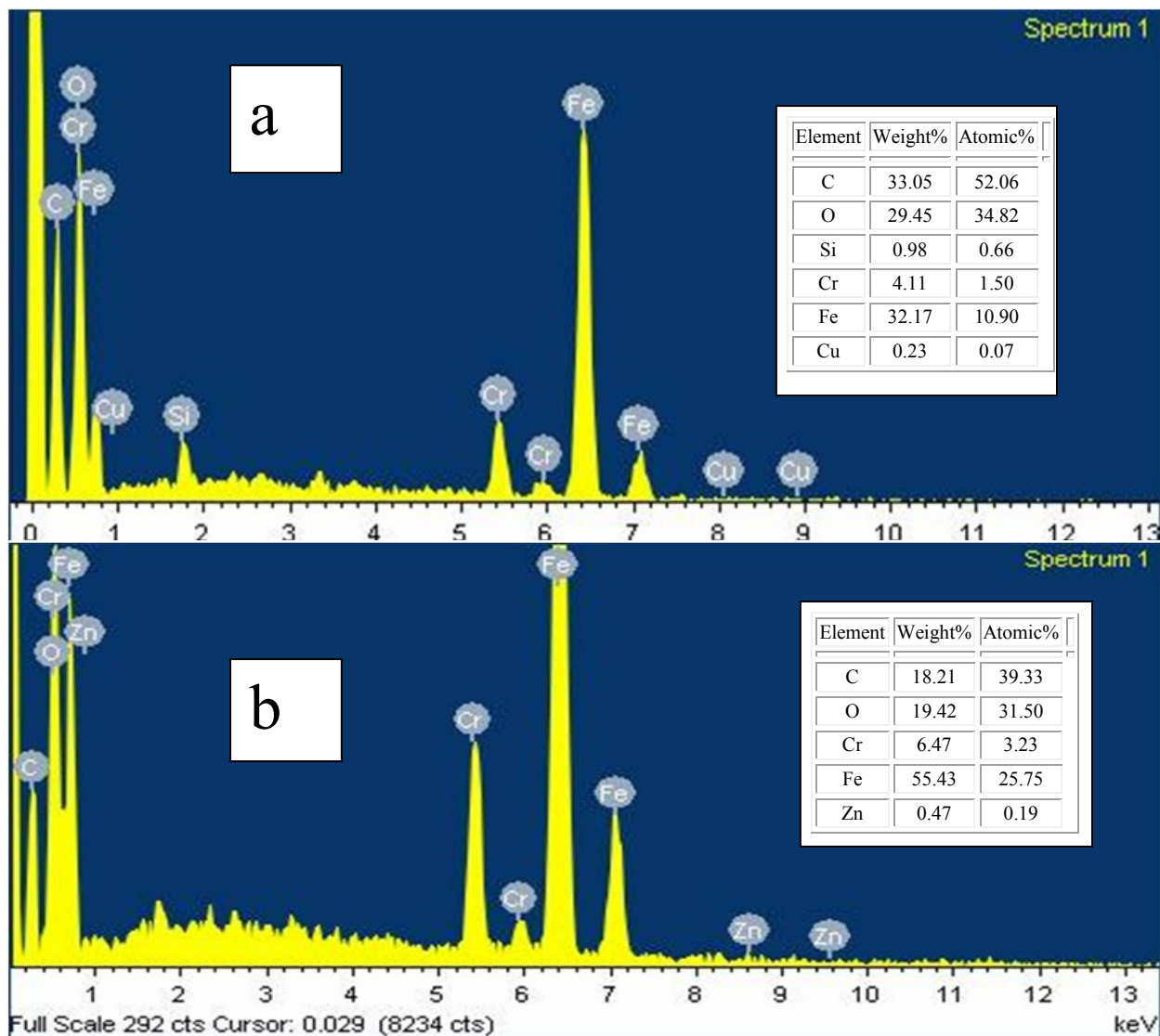


**Figure 6.7** EDS analysis of WEDM samples at  $T_{on}= 120$  units,  $T_{off}= 50$  units,  $SV= 50$  volts and  $WF= 5$  m/min (a) For non treated workpiece (b) For deep cryogenic treated workpiece



**Figure 6.8** EDS analysis of WEDM samples at  $T_{on}= 120$  units,  $T_{off}= 55$  units,  $SV= 50$  volts and  $WF= 7$  m/min (a) For non treated workpiece (b) For deep cryogenic treated workpiece

In non treated workpiece both copper and zinc elements are found in energy dispersive spectroscopy analysis. In deep cryogenic treated workpiece only copper element of brass wire is found because more electric discharge energy is produced relative to non treated workpiece. Due to more discharge energy zinc element is boiled off during machining and flushed out by dielectric medium. Similarly figure 6.8 shows the EDS analysis of WEDM samples at different parameter setting for deep cryogenic treated and non treated workpiece.



**Figure 6.9** EDS analysis of WEDM samples at  $T_{on}= 110$  units,  $T_{off}= 60$  units,  $SV= 60$  volts and  $WF=5m/min$  (a) For non treated workpiece (b) For deep cryogenic treated workpiece

Figure 6.9 indicates the EDS analysis of WEDM machined surface, shows the accumulation of elements of brass wire on machined surface with parameter settings at  $T_{on}= 110$  units,  $T_{off}= 60$  units,  $SV= 60$  volts and  $WF= 5m/min$ .

# Chapter 7

## Optimum Selection of WEDM process by using TOPSIS-AHP Approach

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### 7.1 TOPSIS-AHP Methods

TOPSIS stands for ‘Technique for order preference by similarity to ideal solution’ and AHP ‘Analytical hierarchy process’. This study aims to develop a combination of TOPSIS and AHP methods to solve multi- response parameteric optimization in Wire Electric Discharge Machining. A combined method using ‘technique for order preference by similarity to ideal solution’ and Analytical hierarchy process used to select the most appropriate parameters of WEDM for machining of non treated and deep cryogenic treated AISI D3 tool steel. In this study the weightage for each performance characteristics is calculated by AHP method. The different steps used in these techniques are discussed in detail below.

#### 7.1.1 Decision Matrix

The information related to all alternative experiments is stored in a matrix form  $D = [d_{ij}]_{m \times n}$ , where each row characterizes one experiment based on performance attributes.

$$D = [d_{ij}]_{m \times n} \text{ where } i=1,2,3,\dots,m \text{ and } j=1,2,3,\dots,n \quad (7.1)$$

The 'm' represents the number of alternatives experiments based on parameters settings in row i.e parameter setting of wire EDM. The 'n' represents the no. of attributes i.e performance characteristics. Each row characterize one experiment based on performance characteristics given in table 7.1 .The data given in table 7.1 has been represented as decision matrix  $D_{18 \times 3}$  for both deep cryogenic treated workpiece and non treated workpiece. In this study experiments were performed based on L18 orthogonal array to investigate the effect on performance characteristics i.e material removal rate, surface roughness and percentage of dimensional deviation.

**Table 7.1** Mean data of performance characteristics

Experiment No.	Results for non treated workpiece			Results for deep cryogenic treated workpiece		
	MRR	Surface Roughness	Percentage of dimensional deviation	MRR	Surface Roughness	Percentage of dimensional deviation
1	1.2795	1.045	0.545	1.2845	1.560	0.515
2	0.9150	1.010	0.140	1.1535	1.490	0.105
3	0.7245	1.045	0.465	0.8925	1.440	0.450
4	1.7280	1.165	0.610	2.2030	1.715	0.580
5	1.2585	1.170	0.255	1.7425	1.630	0.225
6	1.0530	1.105	0.355	1.3900	1.600	0.340
7	2.5265	1.270	0.940	3.3195	2.105	0.905
8	1.8335	1.295	0.205	2.4750	1.955	0.170
9	1.6235	1.240	0.350	1.9510	1.790	0.310
10	0.7610	0.965	0.470	1.0110	1.435	0.445
11	0.5970	0.895	0.295	0.7175	1.355	0.260
12	0.4935	0.840	0.360	0.5120	1.210	0.340
13	1.1380	0.980	0.610	1.1165	1.510	0.590
14	0.8620	1.310	0.235	0.9670	1.580	0.200
15	0.7050	0.980	0.180	0.8235	1.470	0.150
16	2.2065	1.220	0.590	2.3305	2.125	0.555
17	1.4355	1.020	0.245	1.6225	1.965	0.215
18	0.9830	0.985	0.160	1.3175	1.695	0.120

The decision matrix for non treated workpiece represented by  $D_1$  and for deep cryogenic represented by  $D_2$ .

$$D_1=[d_{ij}]_{18 \times 3} = \begin{bmatrix} 1.2795 & 1.045 & 0.545 \\ 0.9150 & 1.010 & 0.140 \\ 0.7245 & 1.045 & 0.465 \\ 1.7280 & 1.165 & 0.610 \\ 1.2585 & 1.170 & 0.255 \\ 1.0530 & 1.105 & 0.355 \\ 2.5265 & 1.270 & 0.940 \\ 1.8335 & 1.295 & 0.205 \\ 1.6235 & 1.240 & 0.350 \\ 0.7610 & 0.965 & 0.470 \\ 0.5970 & 0.895 & 0.295 \\ 0.4935 & 0.840 & 0.360 \\ 1.1380 & 0.980 & 0.610 \\ 0.8620 & 1.310 & 0.235 \\ 0.7050 & 0.980 & 0.180 \\ 2.2065 & 1.220 & 0.590 \\ 1.4355 & 1.020 & 0.245 \\ 0.9830 & 0.985 & 0.160 \end{bmatrix} \quad D_2=[d_{ij}]_{18 \times 3} = \begin{bmatrix} 1.2845 & 1.560 & 0.515 \\ 1.1535 & 1.490 & 0.105 \\ 0.8925 & 1.440 & 0.450 \\ 2.2030 & 1.715 & 0.580 \\ 1.7425 & 1.630 & 0.225 \\ 1.3900 & 1.600 & 0.340 \\ 3.3195 & 2.105 & 0.905 \\ 2.4750 & 1.955 & 0.170 \\ 1.9510 & 1.790 & 0.310 \\ 1.0110 & 1.435 & 0.445 \\ 0.7175 & 1.355 & 0.260 \\ 0.5120 & 1.210 & 0.340 \\ 1.1165 & 1.510 & 0.590 \\ 0.9670 & 1.580 & 0.200 \\ 0.8235 & 1.470 & 0.150 \\ 2.3305 & 2.125 & 0.555 \\ 1.6225 & 1.965 & 0.215 \\ 1.3175 & 1.695 & 0.120 \end{bmatrix} \quad (7.2)$$

### 7.1.2 Normalized Matrix

In this step Normalized Matrix (N) is constructed from decision matrix (D). Performance characteristics may have different units and their magnitudes are varying in large range. These attributes are needed to be compared relatively for different applications. Column wise normalization is carried out to represent them in range of 0 to 1 for evaluation. The normalized matrix for non treated workpiece and deep cryogenic treated workpiece represented by  $N_1$  and  $N_2$  respectively.

$$[nij] = [dij / (\sum_{i=1}^m dij^2)^{1/2}]_{m \times n} \quad \text{where } i = 1, 2, 3, \dots, m \text{ and } j = 1, 2, 3, \dots, n \quad (7.3)$$

Where  $[nij]$  represent the normalized matrix.

$d_{ij}$ = Decision matrix based on number of experiments of WEDM.

$m$ = number of alternative experiments of WEDM.

$n$ = number of performance characteristics i.e material removal rate, surface roughness and percentage of dimensional deviation.

$$\begin{matrix}
N_1=[n_{ij}]_{18 \times 3}= & \begin{matrix} 0.2239 & 0.2251 & 0.2924 \\ 0.1601 & 0.2176 & 0.0751 \\ 0.1268 & 0.2251 & 0.2494 \\ 0.3023 & 0.2509 & 0.3272 \\ 0.2202 & 0.2520 & 0.1368 \\ 0.1842 & 0.2380 & 0.1904 \\ 0.4420 & 0.2736 & 0.5042 \\ 0.3208 & 0.2789 & 0.1100 \\ 0.2840 & 0.2671 & 0.1878 \\ 0.1331 & 0.2079 & 0.2521 \\ 0.1045 & 0.1928 & 0.1582 \\ 0.0863 & 0.1809 & 0.1931 \\ 0.1991 & 0.2111 & 0.3272 \\ 0.1508 & 0.2822 & 0.1261 \\ 0.1233 & 0.2111 & 0.0966 \\ 0.3860 & 0.2628 & 0.3165 \\ 0.2512 & 0.2197 & 0.1314 \\ 0.1720 & 0.2122 & 0.0858 \end{matrix} & & \begin{matrix} 0.1835 & 0.2209 & 0.2932 \\ 0.1648 & 0.2110 & 0.0598 \\ 0.1275 & 0.2039 & 0.2562 \\ 0.3147 & 0.2428 & 0.3302 \\ 0.2489 & 0.2308 & 0.1281 \\ 0.1986 & 0.2265 & 0.1935 \\ 0.4742 & 0.2980 & 0.5152 \\ 0.3535 & 0.2768 & 0.0968 \\ 0.2787 & 0.2534 & 0.1765 \\ 0.1444 & 0.2032 & 0.2533 \\ 0.1025 & 0.1918 & 0.1480 \\ 0.0731 & 0.1713 & 0.1935 \\ 0.1595 & 0.2138 & 0.3359 \\ 0.1381 & 0.2237 & 0.1139 \\ 0.1176 & 0.2081 & 0.0854 \\ 0.3329 & 0.3009 & 0.3159 \\ 0.2318 & 0.2782 & 0.1224 \\ 0.1882 & 0.2400 & 0.0683 \end{matrix} & (7.4)
\end{matrix}$$

### 7.1.3 Relative Importance matrix by AHP

Estimation of relative importance of various attributes using pair – wise comparison matrix by the Analytical hierarchy process. The Saaty nine- point scale is adopted for constructing the pair wise matrix as shown in table 7.2. The information is obtained from user or group of experts for the relative importance of one performance characteristic over another. The information is calculated in terms of ratio. Information on all such pair-wise comparison is stored in matrix A, which is  $n \times n$  matrix. In this matrix element  $a_{ij}$  represent the relative importance of  $i^{\text{th}}$  response over  $j^{\text{th}}$  response. The diagonal elements in the matrix A are unity because of their equal importance thus  $a_{ij}=1$ , where  $i=j$ . The relative importance matrix can be represented by equation given below.

$$A = [a_{ij}]_{n \times n}, \text{ where } i= 1,2,\dots,n \text{ and } j=1,2,\dots,n \quad (7.5)$$

$n$ = number of performance characteristics i.e material removal rate, surface roughness and percentage of dimensional deviation.

**Table 7.2** The Saaty rating scale [24]

Intensity of Importance	Definition	Explanation
1	Equal importance	Two factors contribute equally to the objective.
3	Somewhat more important	Experience and judgement slightly favour one over the other.
5	Much more important	Experience and judgement strongly favour one over the other.
7	Very much more important	Experience and judgement very strongly favour one over other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favouring one over other is of highest possible validity.
2,4,6,8	Intermediate values	When compromise is needed

The relative importance matrix A based on users or group of experts is calculated from Satty scale is represented as:

$$A = [a_{ij}]_{3 \times 3} = \begin{vmatrix} 1 & 5 & 7 \\ 1/5 & 1 & 2 \\ 1/7 & 1/2 & 1 \end{vmatrix} \quad (7.6)$$

The Eigen vector method , which modifies the inconsistencies in judgments of relative importance of attributes while making pair wise comparison is used to find out the weights associated with matrix A, i.e.,

$$Ax = \lambda x \quad (7.7)$$

Where  $\lambda$  is Eigen value of A and x is the corresponding Eigen vector. The Eigen vector w is found in following manner:

- Take Eigen vector,  $x_{max}$  corresponding to maximum Eigen value  $\lambda_{max}$  as all the elements are either positive or negative.
- Find the sum of the elements of  $x_{max}$  as

$$\alpha = \sum_{i=1}^n (x_i)_{max} \quad (7.8)$$

- .Find weight vector w as

$$w = (x_{\max})/\alpha \text{ such that } \sum_{i=1}^n w_i = 1 \quad (7.9)$$

$$(A - \lambda_{\max} I) = 0 \quad (7.10)$$

Calculate the max. Eigen value by Matlab  $\lambda_{\max} = 3.0142$  and corresponding different weights  $W_1 = 0.7396$ ,  $W_2 = 0.1666$ ,  $W_3 = 0.0938$ . Consistency Ratio (CR) can be used to check the consistency. If the value of CR is below the threshold of 0.10, then the evaluation of importance of different attributes is considered to be reasonable [24].

$$CR = CI/RI \quad (7.11)$$

$$CI \text{ (Consistency Index)} = \frac{\lambda_{\max} - n}{n - 1} \quad (7.12)$$

Where RI denotes the Random index for  $3 \times 3$  matrix is 0.58 [24]. Consistency Ratio = 0.0071 (less than 0.10).

#### 7.1.4 Weighted Normalized matrix

The weights calculated from the relative importance matrix are applied to the normalized matrix. All the attributes have different importance during the selection of optimum parameter setting of Wire EDM. The weighted normalized matrix represented by V. This matrix combines the relative weights and normalized matrix. With this matrix we calculate the true comparable value of attributes. The matrix  $V_1$  represents the normalized matrix for non treated workpiece and  $V_2$  for deep cryogenic treated workpiece.

$$[V_{ij}]_{m \times n} = [n_{ij}]_{m \times n} \times [w_{ij}]_{1 \times n} \text{ where } i=1, \dots, m \text{ and } j=1, \dots, n \quad (7.13)$$

Where  $V_{ij}$  represent the weighted normalized matrix.

$n_{ij}$  = Normalized matrix for alternative experiments of WEDM.

$w_{ij}$  = Represents the relative weights calculated from relative importance matrix.

The weighted normalized matrix is also called inclusive matrix because it can be represented by combined normalized matrix and weights corresponding to relative importance matrix. The weighted normalized matrix for non treated and deep cryogenic treated workpiece represented by  $V_1$  and  $V_2$  respectively as shown in Eq. 7.13.

$$\begin{aligned}
V_1=[v_{ij}]_{18 \times 3} &= \begin{pmatrix} 0.1656 & 0.0375 & 0.0274 \\ 0.1184 & 0.0362 & 0.0070 \\ 0.0938 & 0.0375 & 0.0234 \\ 0.2236 & 0.0418 & 0.0307 \\ 0.1628 & 0.0420 & 0.0128 \\ 0.1363 & 0.0397 & 0.0179 \\ 0.3269 & 0.0456 & 0.0473 \\ 0.2373 & 0.0465 & 0.0103 \\ 0.2101 & 0.0445 & 0.0176 \\ 0.0985 & 0.0346 & 0.0236 \\ 0.0773 & 0.0321 & 0.0148 \\ 0.0639 & 0.0301 & 0.0181 \\ 0.1473 & 0.0352 & 0.0307 \\ 0.1115 & 0.0470 & 0.0118 \\ 0.0912 & 0.0352 & 0.0091 \\ 0.2855 & 0.0438 & 0.0297 \\ 0.1858 & 0.0366 & 0.0123 \\ 0.1272 & 0.0353 & 0.0081 \end{pmatrix} &
V_2=[v_{ij}]_{18 \times 3} &= \begin{pmatrix} 0.1357 & 0.0368 & 0.0275 \\ 0.1219 & 0.0351 & 0.0056 \\ 0.0943 & 0.0340 & 0.0240 \\ 0.2327 & 0.0405 & 0.0310 \\ 0.1841 & 0.0384 & 0.0120 \\ 0.1469 & 0.0377 & 0.0182 \\ 0.3507 & 0.0497 & 0.0483 \\ 0.2615 & 0.0461 & 0.0091 \\ 0.2061 & 0.0422 & 0.0166 \\ 0.1068 & 0.0338 & 0.0238 \\ 0.0758 & 0.0320 & 0.0139 \\ 0.0541 & 0.0285 & 0.0182 \\ 0.1180 & 0.0356 & 0.0315 \\ 0.1022 & 0.0373 & 0.0107 \\ 0.0870 & 0.0347 & 0.0080 \\ 0.2462 & 0.0501 & 0.0296 \\ 0.1714 & 0.0463 & 0.0115 \\ 0.1392 & 0.0400 & 0.0064 \end{pmatrix} &
\end{aligned} \tag{7.14}$$

### 7.1.5 Ranking and Optimum selection by TOPSIS method

The TOPSIS method is based on the concept that the best possible solution is shortest distance from +ve benchmark and worst solution is at farthest distance from -ve benchmark. The positive-ideal solution of Wire EDM parameter setting is expressed as:

$$\begin{aligned}
V^* &= \{(\sum_i^{max} V_n / j \in J), (\sum_i^{min} V_n / j \in J') / i=1,2,3 \dots N\} & (7.15) \\
&= \{V_1^+, V_2^+, V_3^+, \dots, V_M^+\}
\end{aligned}$$

The negative ideal worst solution is expressed as:

$$\begin{aligned}
V^- &= \{(\sum_i^{min} V_n / j \in J), (\sum_i^{max} V_n / j \in J') / i=1, 2,3 \dots N\} & (7.16) \\
&= \{V_1^-, V_2^-, V_3^-, \dots, V_M^-\}
\end{aligned}$$

Where  $J=(j=1,2,3 \dots, M) / j$  is associated with beneficial attributes, and  $J'=(j=1,2,3, \dots, M) / j$  is associated with non beneficial attributes. The separation for each alternative from positive ideal solution is given by:

$$S_i^+ = [\sum_{j=1}^n (vij - V_j^*)^2]^{1/2} \quad \text{where } i= 1, 2, \dots, m \quad (7.17)$$

The separation from negative ideal solution is given by:

$$S_i^- = [\sum_{j=1}^n (vij - V_j^-)^2]^{1/2} \quad \text{where } i=1, 2, \dots, m \quad (7.18)$$

$V^*$  and  $V^-$  for non treated workpiece is represented as:

$$V^* = (0.3269, 0.0470, 0.0473)$$

$$V^- = (0.0639, 0.0301, 0.0070)$$

Similarly for deep cryogenic treated workpiece:

$$V^* = (0.3507, 0.0501, 0.0483)$$

$$V^- = (0.0541, 0.0285, 0.0056)$$

The separation measures are calculated from Eq. (7.17) to (7.18) for non treated workpiece are shown below:

$S_1^+ = 0.1627$	$S_{10}^+ = 0.2295$	$S_1^- = 0.1036$	$S_{10}^- = 0.0363$
$S_2^+ = 0.2123$	$S_{11}^+ = 0.2519$	$S_2^- = 0.0541$	$S_{11}^- = 0.0128$
$S_3^+ = 0.2342$	$S_{12}^+ = 0.2647$	$S_3^- = 0.0324$	$S_{12}^- = 0.0111$
$S_4^+ = 0.1043$	$S_{13}^+ = 0.1802$	$S_4^- = 0.1615$	$S_{13}^- = 0.0834$
$S_5^+ = 0.1673$	$S_{14}^+ = 0.2179$	$S_5^- = 0.0991$	$S_{14}^- = 0.0491$
$S_6^+ = 0.1927$	$S_{15}^+ = 0.2387$	$S_6^- = 0.0734$	$S_{15}^- = 0.0269$
$S_7^+ = 0.0014$	$S_{16}^+ = 0.0413$	$S_7^- = 0.2662$	$S_{16}^- = 0.2229$
$S_8^+ = 0.0964$	$S_{17}^+ = 0.1456$	$S_8^- = 0.1738$	$S_{17}^- = 0.1219$
$S_9^+ = 0.1200$	$S_{18}^+ = 0.2034$	$S_9^- = 0.1469$	$S_{18}^- = 0.0634$

Similarly the separation measures for deep cryogenic treated workpiece are calculated shown below:

$S_1^+=0.2161$	$S_{10}^+=0.2453$	$S_1^-=0.0840$	$S_{10}^-=0.0549$
$S_2^+=0.2330$	$S_{11}^+=0.2773$	$S_2^-=0.0673$	$S_{11}^-=0.0216$
$S_3^+=0.2576$	$S_{12}^+=0.2986$	$S_3^-=0.0439$	$S_{12}^-=0.0126$
$S_4^+=0.1191$	$S_{13}^+=0.2334$	$S_4^-=0.1802$	$S_{13}^-=0.0681$
$S_5^+=0.1705$	$S_{14}^+=0.2513$	$S_5^-=0.1304$	$S_{14}^-=0.0488$
$S_6^+=0.2061$	$S_{15}^+=0.2670$	$S_6^-=0.0937$	$S_{15}^-=0.0321$
$S_7^+=0.0003$	$S_{16}^+=0.1058$	$S_7^-=0.3001$	$S_{16}^-=0.1944$
$S_8^+=0.0970$	$S_{17}^+=0.1827$	$S_8^-=0.2081$	$S_{17}^-=0.1184$
$S_9^+=0.1481$	$S_{18}^+=0.2156$	$S_9^-=0.1526$	$S_{18}^-=0.0854$

The relative closeness to positive ideal solution is represented by  $C^*$  and is mathematically defined as:

$$C_i^* = S_i^- / (S_i^- + S_i^+) \quad \text{where } i=1,2,\dots,m, (0 \leq C_i^* \leq 1) \quad (7.19)$$

Arrange  $C_i^*$  either in increasing or decreasing order,  $C_i^*$  closest to 1 is most preferred and smallest one is least preferred. Optimum solution ( $C_i^*$  closest to 1) ensures that it is closest to hypothetically best solution and farthest from hypothetically worst solution. The relative closeness coefficient of different alternative experiments of WEDM for non treated workpiece and deep cryogenic treated workpiece are shown table 7.3. The alternatives (experiments) are arranged in descending or ascending order in accordance with values of indices  $C_i^*$  indicating the most preferred and least preferred feasible optimal parameter setting. The value of  $C_i^*$  based on Eq. (7.19) are shown in table 7.3. From these value of index , it is understood that WEDM process parameter designated as alternative experiment 7<sup>th</sup> is the first right choice and alternative 12<sup>th</sup> is last choice for given application under given conditions. The optimal WEDM process parameters of 7<sup>th</sup> alternative are: Pulse on time 120 unit, Pulse off time 50 unit, Spark gap set voltage 50 v0lts, Wire feed 5 m/min. The 7<sup>th</sup> alternative experiment parameters setting are best based on ranking and give the optimum results of performance characteristics.

**Table 7.3** Ranking and  $C_i^*$  values based on TOPSIS method

Experiment No.	For non treated workpiece		For deep cryogenic treated workpiece	
	$C_i^*$ based on TOPSIS method	Ranking	$C_i^*$ based on TOPSIS method	Ranking
1	0.3890	7 <sup>th</sup>	0.2799	10 <sup>th</sup>
2	0.2030	12 <sup>th</sup>	0.2241	12 <sup>th</sup>
3	0.1215	15 <sup>th</sup>	0.1456	15 <sup>th</sup>
4	0.6075	4 <sup>th</sup>	0.6020	4 <sup>th</sup>
5	0.3719	8 <sup>th</sup>	0.4333	6 <sup>th</sup>
6	0.2758	10 <sup>th</sup>	0.3472	8 <sup>th</sup>
7	0.9947	1 <sup>st</sup>	0.9990	1 <sup>st</sup>
8	0.6432	3 <sup>rd</sup>	0.6820	2 <sup>nd</sup>
9	0.5503	5 <sup>th</sup>	0.5074	5 <sup>th</sup>
10	0.1365	14 <sup>th</sup>	0.1828	13 <sup>th</sup>
11	0.0483	17 <sup>th</sup>	0.0722	17 <sup>th</sup>
12	0.0402	18 <sup>th</sup>	0.0404	18 <sup>th</sup>
13	0.3163	9 <sup>th</sup>	0.2258	11 <sup>th</sup>
14	0.1838	13 <sup>th</sup>	0.1626	14 <sup>th</sup>
15	0.1012	16 <sup>th</sup>	0.1073	16 <sup>th</sup>
16	0.8436	2 <sup>nd</sup>	0.6475	3 <sup>rd</sup>
17	0.4557	6 <sup>th</sup>	0.3932	7 <sup>th</sup>
18	0.2376	11 <sup>th</sup>	0.2837	9 <sup>th</sup>

The optimum value of MRR, surface roughness and percentage of dimensional deviation based on ranking for non treated and deep cryogenic treated workpiece are 2.5265mm<sup>3</sup>/min, 1.270  $\mu$ m, 0.940 and 3.3195 mm<sup>3</sup>/min, 2.105  $\mu$ m, 0.905 respectively.

# Chapter 8

## Conclusions and Future scope of work

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### 8.1 CONCLUSIONS

In early chapters, firstly pilot experimentation has been done for select the parameters for main experimentation. The input parameters pulse on time, pulse off time, spark gap set voltage and wire feed rate are investigated to check their effects on performance characteristics. The performance characteristics are material removal rate, surface roughness and percentage of dimensional deviation for non treated and deep cryogenic treated die steel AISI D3. The Minitab 16.0 software is used for analysis of results. The combined TOPSIS-AHP methods are used for optimum selection of parameter setting of WEDM. The conclusions drawn from this study are discussed briefly in this chapter.

#### 8.1.1 Conclusions drawn from pilot study

1. The results of pilot study concluded that pulse on time, pulse off time and spark gap set voltage significantly affects the cutting rate. The wire feed rate has less significant affect on cutting rate.
2. Based on pilot study the range of process parameters for further experimentation concluded as: pulse on time from 110 unit to 120 unit, pulse off time from 50 unit to 60 unit, spark gap set voltage from 50V to 60V and wire feed rate from 3 m/min to 7 m/min.

#### 8.1.2 Conclusions drawn from experimentation of non treated die steel AISI D3

1. The percentage contribution of process parameters for material removal rate are: pulse on time 53.67%, pulse off time 26.09%, spark gap set voltage 14.34% and wire feed rate 0.02%, based on analysis of mean data the input parameters pulse on time, pulse off time and spark gap set voltage are significant factors that will affect the material removal rate.

2. The percentage contribution of process parameters for surface roughness are: pulse on time 39.82%, pulse off time 7.50%, spark gap set voltage 21.55% and wire feed rate 13.55% ,based on analysis of mean data result shows that pulse on time, spark gap set voltage and wire feed rate are significant factors that will affect the surface roughness.
3. The percentage contribution of process parameters for percentage of dimensional deviation are: pulse on time 0.79%, pulse off time 71.19%, spark gap set voltage 3.86% and wire feed rate 0.65%, based on analysis of mean data pulse off time is significant factor that will affect the dimensional deviation.

### **8.1.3 Conclusions drawn from experimentation of deep cryogenic treated die steel AISI D3**

1. The percentage contribution of process parameters for material removal rate are: pulse on time 52.58%, pulse off time 17.91%, spark gap set voltage 22.12% and wire feed rate 0.33%, based on analysis of mean data the input parameters pulse on time, pulse off time and spark gap set voltage are significant factors that will affect the material removal rate.
2. The percentage contribution of process parameters for surface roughness are: pulse on time 77.02%, pulse off time 11.80%, spark gap set voltage 4.40% and wire feed rate 1.84%, based on analysis of mean data result shows that pulse on time, spark gap set voltage and pulse off time are significant factors that will affect the surface roughness.
3. The contribution of input process parameters for percentage of dimensional deviation are: pulse on time 0.45%, pulse off time 70.87%, spark gap set voltage 3.85% and wire feed rate 0.71%, based on analysis of mean data pulse off time is significant factor that will affect the dimensional deviation.

### **8.1.4 Conclusions drawn from comparison of results for non treated and deep cryogenic treated die steel AISI D3**

1. Experimental results showed that material removal rate is increased up to 21.27% after deep cryogenic treatment. The material removal rate is increased due to increase in discharge energy during machining.

2. Surface roughness is significantly affected by deep cryogenic treatment and the results shows that surface roughness is increased up to 34% as compared to non cryogenic workpiece based on experimental data.
3. The percentage of dimensional deviation is decreased upto 7.62% after deep cryogenic treatment based on experimental data. This indicates that the dimensional stability of WEDM is increased after deep cryogenic treatment.

### **8.1.5 Conclusions drawn from Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopy (EDS)**

1. The scanning electron microscope (SEM) of selected samples has been done for average recast layer thickness. It has been concluded from the results that average recast layer thickness is increased after deep cryogenic treatment because large amount of discharge energy is produced during machining in cryogenic workpiece as compared to non cryogenic workpiece.
2. The SEM micrographs showed that average recast layer thickness is significantly affected by pulse on time, pulse off time and spark gap set voltage. Results indicates that average recast layer thickness is increased with increase in pulse on time and decreased with increase in pulse off time and spark gap set voltage. The average recast layer thickness is 26.38% decreased with increase in pulse off time from 50 units to 55 units for deep cryogenic treatment and for non cryogenic workpiece decrease in average recast layer thickness is 38.3%.
3. The Energy dispersive spectroscopy (EDS) of WEDM samples indicates the accumulation of brass wire elements on the machined surface. Cu and Zn were observed on the machined surface for non cryogenic work pieces. Only Cu element was observed on the machined surface for deep cryogenic treated work piece. This may be due to more electric discharge energy is produced relative to non cryogenic workpiece.

### **8.1.6 Conclusions drawn from TOPSIS-AHP approach**

1. The coefficient of closeness found to be maximum at the experiment conditions corresponding to pulse on time: 120 unit (1.1  $\mu$ s), pulse off time: 50 unit (36  $\mu$ s),

spark gap set voltage: 50 volts and wire feed rate 5 m/min respectively, so these are the optimum parameters setting of WEDM.

2. The optimum value of MRR, surface roughness and percentage of dimensional deviation based on ranking for non treated and deep cryogenic treated workpiece are 2.5265mm<sup>3</sup>/min, 1.270 μm, 0.940 and 3.3195mm<sup>3</sup>/min, 2.105 μm, 0.905 respectively.

## **8.2 Future scope of work**

The different issues, which can be further studied in future research work are discussed as:

1. The material should be cold cryogenic treated and shallow cryogenic treated for further investigation of WEDM.
2. The analysis of results can be done by other optimization techniques and their results can be compared.
3. The residual stress developed after the wire electric discharge machining can further be investigated.
4. The machinability of advance materials MMC and other composites are investigated on WEDM.

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## Appendices

**Table A: Conversion table for pulse on time**

Pulse on time (machine units)	Pulse on time ( $\mu\text{s}$ )	Pulse on time (machine units)	Pulse on time ( $\mu\text{s}$ )	Pulse on time (machine units)	Pulse on time ( $\mu\text{s}$ )	Pulse on time (machine units)	Pulse on time ( $\mu\text{s}$ )
100	0.1	108	0.5	116	0.9	124	1.3
101	0.15	109	0.55	117	0.95	125	1.35
102	0.2	110	0.6	118	1.0	126	1.4
103	0.25	111	0.65	119	1.05	127	1.45
104	0.3	112	0.7	120	1.1	128	1.5
105	0.35	113	0.75	121	1.15	129	1.55
106	0.4	114	0.8	122	1.2	130	1.6
107	0.45	115	0.85	123	1.25	131	1.65

**Table B: Conversion table for pulse off time**

Pulse off time (machine units)	Pulse off time ( $\mu\text{s}$ )	Pulse off time (machine units)	Pulse off time ( $\mu\text{s}$ )	Pulse off time (machine units)	Pulse off time ( $\mu\text{s}$ )	Pulse off time (machine units)	Pulse off time ( $\mu\text{s}$ )
0	2	16	6	32	10	48	22
1	2.25	17	6.25	33	10.5	49	24
2	2.5	18	6.5	34	11	50	26
3	2.75	19	6.75	35	11.5	51	28
4	3	20	7	36	12	52	30
5	3.25	21	7.25	37	12.5	53	32
6	3.5	22	7.5	38	13	54	34
7	3.75	23	7.75	39	13.5	55	36
8	4	24	8	40	14	56	38
9	4.25	25	8.25	41	14.5	57	40
10	4.5	26	8.5	42	15	58	42
11	4.75	27	8.75	43	16	59	44
12	5	28	9	44	17	60	46
13	5.25	29	9.25	45	18	61	48
14	5.5	30	9.5	46	19	62	50
15	5.75	31	9.75	47	20	63	52