

**INVESTIGATION ON EFFECTS OF UNTREATED AND
CRYOGENICALLY TREATED BRASS WIRE ON M42 HSS IN
WEDM PROCESS**

**A thesis submitted
in fulfilment of the requirements
for the award of the degree
of**

**MASTER OF ENGINEERING
IN
PRODUCTION ENGINEERING
by**

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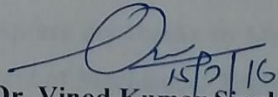
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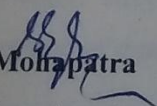
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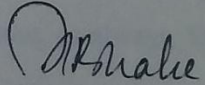
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Ranjit Singh
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ABSTRACT

M42 High speed steel is a finest cobalt based high speed steel having high hot hardness and better hot hardness. These properties makes this steel an outstanding option for machining high-strength and pre-hardened steels, high-hardened alloys, and the difficult-to-machine, nonferrous super alloys used in the aerospace, oil, and power generation industries. Its applications are twist drills, milling cutters, taps, reamers, broaches, saws, knives, and thread rolling dies. The inherent problem of machining these high speed steels with conventional machining processes necessitate the use of alternative machining processes. The wire electrical discharge machining(WEDM) processes has been found to be a good alternative of conventional machining processes. Less work has been reported for predicting the performance of WEDM processes particularly for the M42 HSS. In the present work, the effect of shallow cryogenated brass wire on the M42 HSS is compared with the results of untreated wire on M42. The empirical modeling of process parameters of the WEDM has been carried out for the M42 HSS using a well known experimental design approach called Response Surface Methodology(RSM). The parameters such as pulse-on, pulse-off, spark gap voltage and wire feed have been selected as input variables keeping current and wire tension constant. The performance has been measured in terms of cutting speed(CS), surface roughness(Ra) and dimensional deviation(DD).

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LIST OF SYMBOLS AND ABBREVIATIONS

A	:	Ampere
Al	:	Aluminum
ANOVA	:	Analysis of variance
apx	:	Approximately
avg.	:	Average
BBD	:	Box-Behenken Design
BHN	:	Brinell's Hardness Number
BPNN	:	Back Propagation Neural Network
C	:	Carbon
CCD	:	Central Composited Design
CI	:	Confidence Interval
cm	:	Centimeter
CNC	:	Computer Numerical Control
Co	:	Cobalt
Cr	:	Chromium
CS	:	Cutting Speed
DD	:	Dimensional Deviation
di	:	Standardized residual
dia.	:	Diameter
DOE	:	Design Of Experiment
dof	:	Degree of freedom
e	:	Residual (error)
e_i	:	i^{th} residual
$e_{(i)}$	:	Prediction error (Press or deleted residual)
EDM	:	Electrical Discharge Machining
expt.	:	Experiment
FCC	:	Face Centered Cubic
Fe	:	Iron
g	:	Gram
GA	:	Genetic Algorithm
Ga	:	Gallium
Ge	:	Germanium
GMAW	:	Gas Metal Arc Welding
GPa	:	Giga Pascal
GRA	:	Grey Relational Analysis
HCHCr	:	High Carbon High Chromium
HH	:	Half Hard
hii	:	Measure of the location of i^{th} point in x-space
HP	:	High Pressure
HSS	:	High Speed Steel

HSLA	:	High Strength Low Alloy
HV	:	Hardness (Vicker's)
Hz	:	Hertz
i	:	i th observation, variable, residuals etc.
Ig	:	Gap current
Ip	:	Peak current
k	:	Number of factors
Kbar	:	Kilobar
Kg	:	Kilogram
KVA	:	Kilo-Volt –Ampere
LOF	:	Lack Of Fit
LBM	:	Laser Beam Machining
Mn	:	manganese
m	:	Meter
max	:	Maximum
min	:	Minimum
mm	:	Millimeter
MMC	:	Metal Matrix Composite
Mo	:	Molybdenum
MPa	:	Mega Pascal
MRR	:	Material Removal Rate
MS	:	Mean Square
MS _R	:	Mean Square Regression
MS _{Res}	:	Mean Square Residual
mu	:	Machine unit
n	:	Number of observation
Nb	:	Niobium
Ni	:	Nickel
NSGA	:	Non-dominated Sorting Algorithm
OA	:	Orthogonal Array
P	:	Phosphorus
PRESS	:	Prediction Error Sum of Squares
Ra	:	Average roughness
RC	:	Resistance-Capacitance
ri	:	Studentized residual
RSM	:	Response Surface Methodology
Rt	:	Maximum roughness
S	:	Sulphur
s	:	Second
SEM	:	Scanning Electron Microscopy
SF	:	Surface Finish
Si	:	Silicon
SiC	:	Silicon Carbide
S-N	:	Signal-to-Noise
SS _{PE}	:	Sum of Squares of pure error
SS _{LOF}	:	Sum of Squares of lack of fit

SS_R	:	Sum of Squares regression
SS_{Res}	:	Sum of Squares of residual
SS_T	:	Total Sum of Squares
SV	:	Spark gap voltage
Ta	:	Tantalum
Ti	:	Titanium
ti	:	R-student
TIG	:	Tungsten Inert Gas
T_{off}	:	Pulse off time
T_{on}	:	Pulse on time
TWR	:	Tool Wear Ratio
USM	:	Ultra Sonic Machining
V	:	Volt
VMRR	:	Volumetric Material Removal Rate
Vol	:	Volume
W	:	Watt
WEDM	:	Wire Electrical Discharge Machining
WF	:	Wire Feed
WLT	:	White Layer Thickness
WT	:	Wire Tension
wt	:	Weight
WWR	:	Wire Wear ratio
x	:	Independent variable (factor)
x_i	:	i^{th} independent variable (factor)
XRD	:	X-Ray Diffraction
y	:	Output response
y_i	:	Value of i^{th} response
$\bar{y}$	:	Average of y_i
$\hat{y}_i$	:	Fitted value of y_i
$\hat{y}_{(i)}$	:	Fitted value of the i^{th} response based on all observations except the i^{th} one
Zn	:	Zinc
2-D	:	2-Dimensional
3-D	:	3-Dimensional
μ	:	Micro
Ω	:	Ohm
A	:	Significance level
B	:	Regression coefficients
σ^2	:	Variance
ε	:	Random error

CHAPTER 1

INTRODUCTION

With the improvement in the innovation, the researchers and technologists in the field of manufacturing are facing new and more challenges. Going with the advancement of mechanical industry, the need for the alloys materials having high hardness, toughness and force resistance are growing day by day. Technically advanced industries such as nuclear power reactors, aeronautics and automobile industry have been demanding elevated strength temperature resistant materials having high strength to weight ratio. The traditional machining processes, in spite of present technical advancements, are insufficient and poor to machine intricate shapes in rigid, die steel and elevated strength temperature resistant alloys. By keeping all these necessities into mind, a number of Non-traditional machining (NTM) processes have been developed. These can be classified according to the type of energies used,

- (1) Mechanical Processes: In the mechanical processes metal exclusion takes place by erosion mechanism where large velocity particles are used as transfer media for the material removal process and hydraulic pressure acts as source of energy. It includes Ultrasonic Machining(USM), Abrasive Jet Machining(AJM) and Water Jet Machining(WJM) etc.
- (2) Chemical Processes: It involves the use of resistant material (acidic or alkaline in nature) to certain portion of the work-piece. The quantity of material which we preferred to remove is removed from the remaining area of work surface by the subsequent application of an etchant that converts the work-piece material into a dissolvable metallic salt. It includes chemical machining(CM), photochemical machining(PCM) etc.
- (3) Electrochemical Processes: It involves the removal of metal by the use of mechanism of ion displacement. High current is required as the source of energy and electrolyte acts as transport media. It includes Electrochemical Machining(ECM), Electro Chemical Grinding(ECG), and Electro- Jet Drilling(EJD) etc.

- (4) **Thermal Processes:** It involves the application of very intense confined heat. Here melting or vaporizing of the small areas at the surface of the work piece removes the material. The source of energy used here is amplified light radiation (Laser Jet Machining(LJM)), high voltage (Electric discharge machining(EDM)) and ionized material (Iron Beam Machining(IBM) and Plasma Arc Machining(PAM)).

In such conditions, conventional machining processes may not be viable, satisfactory or inexpensive due to the following features:

- a) There is a direct mechanical contact between the tool and the work piece.
- b) The tool must be harder than the work piece.
- c) It is difficult to machine complex shapes and obtain close tolerances.

1.1 INTRODUCTION OF EDM PROCESS

The history of electrical discharge machining (EDM) goes back to 1770 with the discovery of the erosive effect of electrical discharges on the cathode surface by English scientist Joseph Priestley. The relaxation circuit for the first die sinking machine was invented in the year 1943 and the gap width between the tool and the work piece was maintained with reduced arcing effect by using servo controller (Abdel and EI-Hofy, 2005).

Electro Discharge Machining (EDM) is an electrothermal non-conventional machining process, where electrical energy is utilized to create an electrical spark and the material exclusion mainly occurs owing to the thermal energy of the spark.

EDM is primarily used to machine the difficult-to-machine materials, high strength material and temperature resistant alloys.

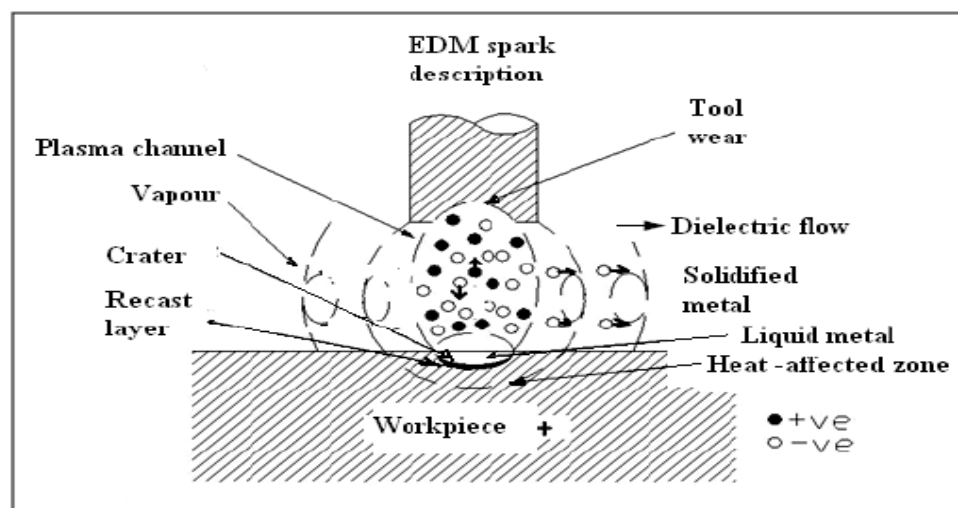


Fig 1.1: Machining view of EDM

1.2 HIGH SPEED STEELS(HSS)

High speed steels are self hardening steels alloyed with W, Mo, Co, V and Cr. They exhibit red hardness, which permits tool to cut at a dull red heat without loss of the hardness or rapid blunting of the cutting edge. It has excellent fracture toughness, fatigue and shock resistance. HSS is very commonly used for geometrically complex rotary tools such as drills, reamers, taps and end mills. Plain HSSs are broadly classified as T-type steels, which have tungsten as the major alloying element and M-type steels which have molybdenum as the major alloying element. M-types are most widely used for rotary tooling, especially drills, end-mills and taps. M-42 has the greatest hot strength [Metal Cutting Theory and Practice by David A. Stephenson, John S. Agapiou]. M42 super high speed steel is a premium cobalt high speed steel with a chemical composition intended for high hardness and better hot hardness. These properties make the steel an outstanding option for machining high-strength and pre-hardened steels, high-hardened alloys, and the difficult-to-machine, nonferrous super alloys used in the aerospace, oil, and power generation industries. M42 exhibits brilliant wear resistance by virtue of elevated heat-treated hardness (68 to 70 HRC), and the high cobalt content impart the hot hardness. As such, the cutting edges on tools finished from M42 super high speed steel(HSS) stay sharp and hard in heavy-duty and high-production cutting application. Its applications are twist drills, milling cutters, taps, reamers, broaches, saws, knives, and thread rolling dies.

1.3 WIRE ELECTRIC DISCHARGE MACHINING

Wire electric discharge machining was initially accessible to the manufacturing industry in late 1960s [Jameson, 2001]. It absolutely was just towards the ending of 1970s, when computer numerical control (CNC) framework introduced into WEDM that has bring up a major development of the manufacturing operation. Due to this WEDM process were broadly explored for any throughout hole machining application. Its extensive capabilities have allowed it to encompass production in the aerospace and automotive industries and almost all areas of conductive material machining [Spedding and Wang, 1997]. This is because wire EDM provides the best substitute, or sometimes the sole alternative, for machining conductive, exotic and high intensity and temperature resistance (HSTR) materials with the scope of generating intricate shapes and profiles [Puri and Bhattacharya, 2003a,b; Joshi and Das, 2010].

1.3.1 Process principle of wire electric discharge machining

WEDM employs continuously moving electrode in the shape of a wire. As recorded in the figure 1.2, wire is acting on upper spool which is to be feed upon the workpiece, and after the wire is used it is brought up on the lower spool. Wire electrode formed of different materials (Brass, Cu, zinc coated, diffusion annealed etc.) which have diameter ranging from 0.05-0.35mm. The opening between the wire and the work piece is flooded with de-ionised water, which behaves as a dielectric. The matter is detached from the succession of electrical discharges [Mcgeough, 1988]. The wire is held straight by a mechanical tensioning device and is fed into the workpiece by a numerically controlled mechanism or a microprocessor. A varying degree of taper ranging from 15° for a 100 mm thick to 30°

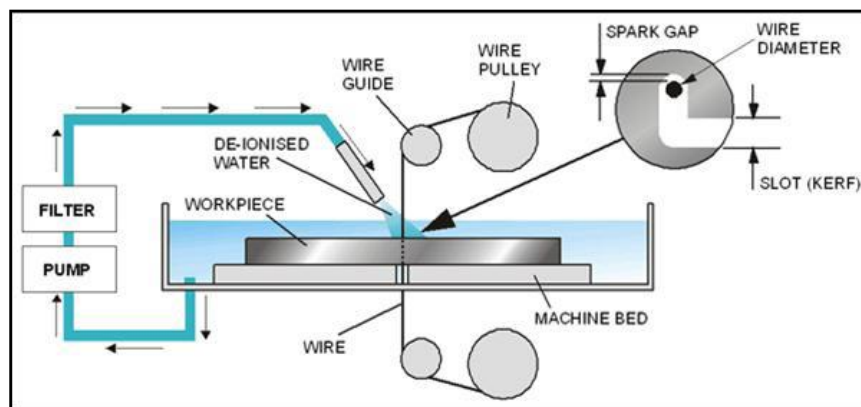


Figure 1.2 Schematic diagram of WEDM system [Guitrau, 1997]

for a 400 mm thick work piece which can be obtained on the cut surface using microprocessor control [Benedict, 1987]. The power supply of an EDM process ought to be capable to check the parameters of current, voltage, duration and frequency of a pulse. Superior features included are the counter electrolysis circuitry that prevents the danger of electrolysis while cutting workpieces that are in the machine for extensive periods. De-ionized water serves as the dielectric in a Wire Electric Discharge Machining(WEDM). The function of dielectric in serving as a medium for discharging is significant. It serves a double role both as an insulator and a conductor. Preceding to the discharge, de-ionized water acts as an insulator, permitting the electrical potential between the wire and work piece to be built to a certain intensity without draining it off throughout the fluid [Roger, 2010]. Dielectric also performs extra functions such as solidifying and flushing away the unwanted debris as well as it keeps the wire and work piece cool. The role of discharge channel is vital in assuring that each discharge cycle must be similar else difference in cutting speed, surface roughness and width of slot may be observed. Thus, maintaining a

definite condition of the de-ionized water dielectric is essential to obtain consistent results from WEDM. Dielectric gets impure by the debris removed, which consists of the metal removed from the workpiece as well as worn out metal from the wire. In order to maintain and preserve the quality of the dielectric fluid, wire-EDM uses mechanical and chemical filtration processes.

1.3.2 Material removal mechanism in WEDM process

The WEDM process is described as:

Step: 1- As shown in Figure.1.3, the spark is initiated by power supply, which generates volts and amperes. The voltage and amperage direct the spark between the wire electrode and the workpiece. The de-ionized water surrounds wire electrode and work material.

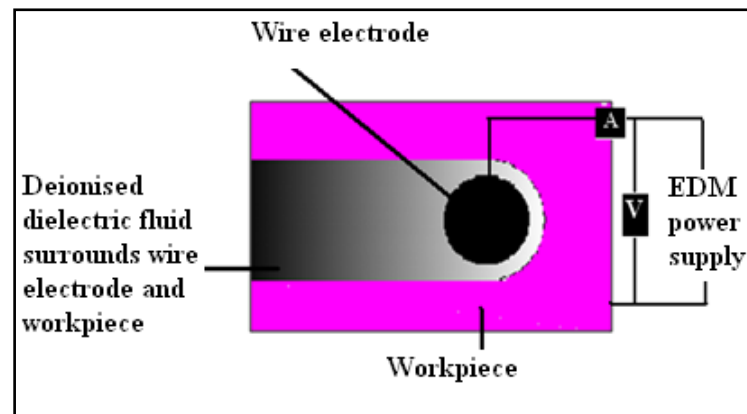


Figure 1.3 Schematic diagram of power supply [Guitrau, 1997]

Step: 2- During the pulse on time duration, the dielectric fluid behaves like a resisting medium until sufficient voltage is given. The dielectric ionizes, due to which spark formation occur between wire and the work material. Controlled spark melts and vaporizes the workpiece material precisely (Figure. 1.4).

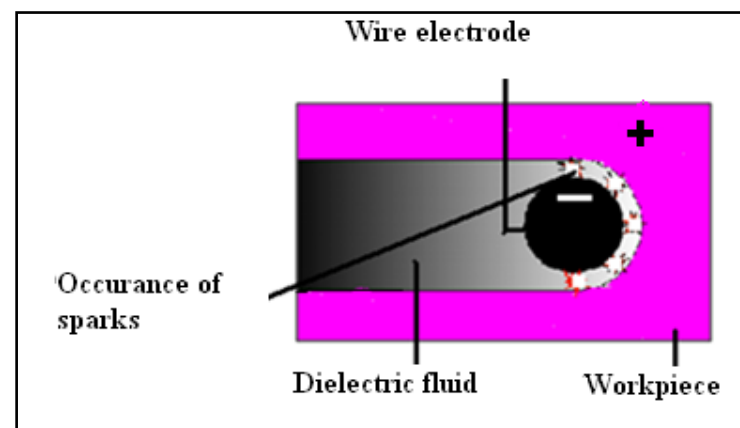


Figure 1.4 Plan diagram of occurrence of sparks [Guitrau, 1997]

Step: 3 - The sparking process is finished during the pulse-off cycle time. The pressurized dielectric fluid instantaneously cools the material and the eroded and worn particles are flushed out (Figure. 1.5).

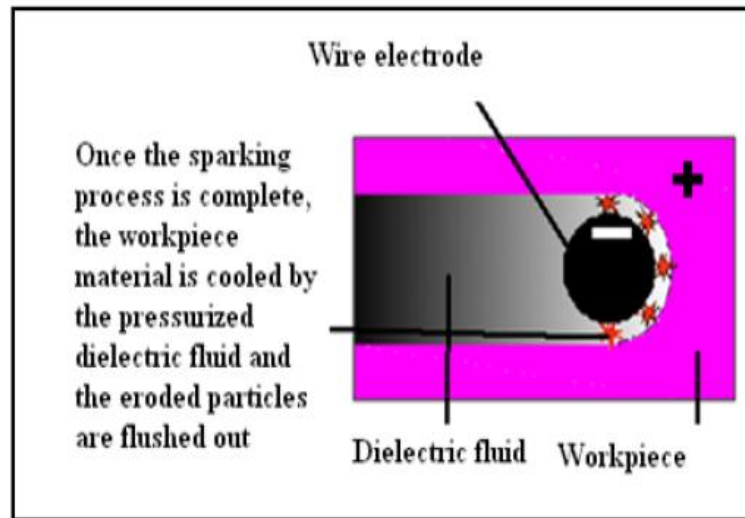


Figure 1.5 Schematic of cooling of the workpiece by the pressurized fluid [Guitrau, 1997]

Step: 4 -The pressurized dielectric fluid flushes away the debris and quenches the surface of the workpiece. The debris are collected by the filtration system of Wire Electric Discharge Machining(WEDM) (Figure. 1.6).

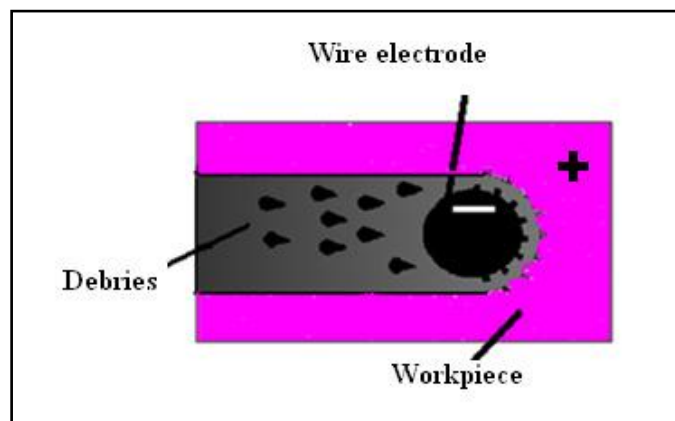


Figure 1.6 Schematic diagram of removal of eroded particles [Guitrau, 1997]

1.3.3 Process capabilities

The capabilities of Wire Electric Discharge Machining(WEDM) process are as follows:

1. WEDM process provides an efficient solution for machining of materials like titanium, tungsten carbide, molybdenum and zirconium with complex shapes and

profiles, which are not easy to machine by conventional machining methods [Sarkar et al., 2008].

2. It is proficient of achieving very small corner radii as it utilize a wire electrode of very small diameter (0.03-0.3 mm).
3. Mechanical stresses are eradicated because no direct contact between the tool and workpiece.
4. The movement of the work piece is controlled by computer numerical control system and wire is fed constantly through the work piece by a micro processor, enabling parts of intricate shapes to be machined with high accuracy [Rao and Pawar, 2010].
5. It eliminates the need for pre-shaped electrodes, which are usually required in sinking EDM to perform roughing and finishing operations.

1.3.4 Applications of WEDM

1. Tool and Die Making Industries
2. Medical and Surgical Industries
3. Aircraft and Aerospace Industries
4. Automobile Industries
5. General applications include prototypes, printer parts, bottling industries, keyways etc

1.3.5 Advantages of wire electric discharge machining(WEDM)

1. It can machine any complex shape in electrically conductive materials irrespective of their melting points, hardness, toughness or brittleness.
2. It generate high surface finish.
3. It make simpler the fabrication of precision work pieces.
4. It avoid wastages and rejections due to early planning and checking of the program.
5. There is no direct contact between the wire and work piece, eliminating the mechanical stresses during machining.
6. WEDM process result into formation of a sharp, burr-free edge, so it becomes extremely desirable machining process choice for work pieces such as medical implant and die openings.
7. Heat treatment is generally unnecessary.

1.3.6 Disadvantages of WEDM

1. Its application is restricted to small thicknesses and conductive materials.
2. Material removal rate is reasonably low.

3. Electrolysis can occur in a few materials.
4. Not suitable for very big work pieces.
5. High capital price.
6. Precision uniform wire is essential

1.4 OVERVIEW OF CRYOGENIC PROCESSING

Cryogenic processing is the method of cooling a material to temperatures far below room temperature. For centuries, the Swiss used to progress the quality of steel by keeping it in the cold regions of Alps for long period of time. Swiss attained the reputation for producing higher grade of steel by carrying out this secret process. The process of experimentation and noticing the effect of cryogenic treatment of steels started during world war-II at the Watertown Arsenal in Watertown, Massachusetts. The process was not computer controlled, so material was immersed into liquid nitrogen for small period of time, allowed to warm up and put into service.

1.5 CRYOGENIC CYCLE

A typical cryogenic cycle consists of:

□ Ramp Down

A distinctive cryogenic cycle brings the temperature of the chamber down up to -196°C over a period of 4-10 hours. Huge stresses are developed during cooling with liquid nitrogen. Slow ramp down prevent thermal shocking of parts.

□ Soaking Stage

A typical soak segment hold the temperature up to -196°C over a period of 8- 40 hours depending on the machine settings for peculiar type of material. During the soak segment of the process the temperature is constantly maintained at a low temperature. The total energy in the structure is higher, if there are vacancies or dislocations in the structure. Precipitation of fine carbides occurs during slow cooling and also, it provide crystal structure to react to the less temperature and allow the energy to depart the crystal structure. By keeping parts at a very low temperature for a long period of time, it is noticed that some energy leaves the lattice and create a more perfect and therefore stronger structure.

□ Ramp Up

A ramp up section brings the temperature back to room temperature. This can typically take 4-20 hours.

□ Temper Ramp Up

A typical temper section ramps the temperature up to a prearranged level over a period of time. Tempering is important with only ferrous materials. During cryogenic treatment, the retained austenite is altered into martensite. This martensite is brittle and it has to temper back to lessen its brittleness. The temper ramp up gradient is kept low.

□ Temper Hold

The whole part has had the benefit of tempering by holding the temperature for about three hours. A distinctive temperature hold time depends on the geometry of the component. There may be more than one temper sequence for a given part or metal.

1.6 TYPES OF CRYOGENIC TREATMENT

□ Deep and Shallow Cryogenic Treatment

Cryogenic treatment is done in a chamber, where the materials to be treated are steadily lowered in temperature from room temperature. Deep cryogenic treatment is

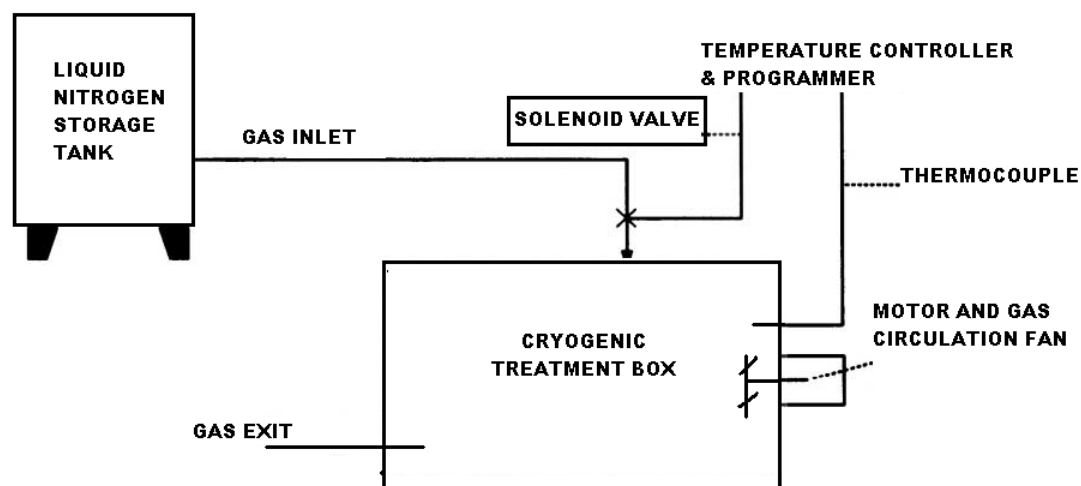


Fig 1.7: View of Cryogenic Processor

carried out at -180°C to -196°C for 18-24 hours, where as shallow cryogenic treatment is performed at around -110°C for 4-8 hours. The materials are then gradually raised to room temperature. Ferrous materials are generally annealed at about 149°C for several hours after cryogenic treatment in the same chamber. Figure above signifies the cryogenic equipment. It includes an insulating box, one motor with a circulating fan, and one thermocouple to measure the cryogenic temperature during operation. The insulating box is connected to the temperature controller, a programmer, liquid nitrogen tank and a solenoid valve to control the gas inlet.

☐ **Cold Treatment**

Cold treatment is done at the temperature of -70°C in the cryogenic chamber. The processing cycle for cold treatment is alike as that of shallow cryogenic treatment. The cold treatment is usually carried out for cutting tools used for machining operations.

1.7 APPLICATIONS OF CRYOGENIC TREATMENT

The cryogenic treatment has been broadly accepted as a cost reduction and performance enhancing technology. The stress relieving benefits achieved due to cryogenic treatment are utilized to authorize the fabrication of critical tolerance parts. The cryo-processing of cold worked tool steel improves wear resistance, toughness and increases life of tools. The cryo-processing has been found to increase the tool life of high speed steels (HSS) from 65% to 343% depending on the cutting conditions utilized. The cryogenic treated tungsten carbide inserts have been found to appreciably enhanced the tool life and get better flank wear resistance. The new studies and research activities about the use of cryogenic treatment to enhance the properties of copper and their alloys have turn up. The improvements in the properties of following components have been observed after cryogenic treatment.

- ☐ Musical instruments
- ☐ Agricultural tooling
- ☐ Tooling industry
- ☐ Electrical components
- ☐ Aerospace/Aircraft components etc.

1.8 ADVANTAGES OF CRYOGENIC TREATMENT

Wide ranges of materials are cryogenic treated to attain good results. The effect of treatment on materials depends on the kind of material. One of the important characteristics of cryogenic treatment is that they enduringly affect the whole mass of components. The cryogenic treatment is environmentally friendly. No waste or residue is created during the process. The major advantages of the process are as follows:

- ☐ Reduces consumption of cutting tools owing to enhanced wear resistance
- ☐ Improves dimension firmness of metal alloys and carbides
- ☐ Stress relieving of components after cryogenic treatment
- ☐ 5-8% increase in conductivity
- ☐ Enhanced machinability of hard to machine materials

1.9 DIELECTRIC FLUID

In EDM, as it has been discussed earlier, material removal mostly occurs due to thermal evaporation and melting. As thermal processing is essential to be carried out in absence of oxygen so that the process can be controlled and oxidation avoided. Oxidation frequently leads to poor surface conductivity of the workpiece hindering further machining. Hence, dielectric fluid should endow with an oxygen free machining environment. Usually kerosene and deionised water is used as a dielectric fluid in EDM. Tap water cannot be used as it ionizes too early and thus break down due to the presence of salts as impurities occur. Dielectric medium is normally flushed around the spark zone. It is also applied through the tool to attain efficient removal of molten material.

1.10 OBJECTIVE OF THE PRESENT STUDY

The study was intended to investigate the machining characteristics of M42 High Speed Steel under the diverse parametric conditions in wire electric discharge machining(WEDM) by using untreated and cryogenated treated brass wire and to model these for their application in the different manufacturing industry.

1.11 SCOPE OF WORK

The work has been restricted to Wire Electrical Discharge Machining of M42 HSS as work material under the different experimental conditions by varying the different

process parameters such as pulse on time(T_{on}), pulse off time(T_{off}), spark gap voltage(SV), wire feed(WF) rate setting and using suitable optimization technique. The results acquired have been modeled for their application in manufacturing industry.

1.12 PHASES OF RESEARCH

- Literature review
- Experimental Set up and Process Parameters Selection
- Design of experiment
- Experimentation work, Result and Discussion
- Optimizing the results

1.12.1 Design of Experiment

The Response Surface Methodology (RSM) is used here for the designing and planning the experiments.

1.12.2 Experimentation work

The experimentation has been done on Computer Numerical Control(CNC) wire electrical discharge machining set-up on M42 HSS as work material, so as to find out the impact of machining parameters i.e pulse on time (T_{on}), pulse off time (T_{off}), spark gap voltage (SV) and wire feed rate (WF) on cutting speed, surface quality and dimension deviation.

1.12.3 Optimizing the Results

The results obtained have been optimized using desirability approach.

1.13 ORGANIZATION OF THE THESIS

The thesis has been divided into the six chapters. Brief description of the contents of every chapter has been given as following:

Chapter: 1 consists of introduction to non-traditional machining methods, EDM, wire EDM process, the process capabilities, application and advantages of the Wire EDM process. Various aspects of WEDM process, including the fundamental principle, material removal mechanism and its restrictions have also been included. Overview of cryogenic treatment, cryogenic processor, its advantages and applications have also been included. Overview about high performance electrodes have also been included. Objectives, scope and the overall methodology of the work have also been described.

Chapter: 2 contains detailed literature review on the research work reported in the past by the various researchers in the field of WEDM. Literature review moreover presents a discussion on the various optimization techniques used by the different researchers. This chapter also includes the literature view about different electrodes, cryogenic treatment in WEDM and surface integrity aspects of WEDM surface which rely on the surface topography and surface metallurgy. Gaps in the literature review have also been identified.

Chapter: 3 contain the experimental set up used in the thesis work. It include all the instruments and machines used for performing the work.

Chapter: 4 provide an overview of the different methods of experimental design. Box – Behnken design(BBD) and response surface methodology(RSM), the different methods and approaches used in the present study are then presented in detail. The speculative aspects of model adequacy building and checking by means of regression analysis are also discussed.

Chapter: 5 outlines the parametric influence on the response measures along with the surface plots and line diagrams. The Multi response optimization of the process parameters using the desirability approach is then presented. Thereafter, results of the confirmatory experiments are presented over here. The surface integrity of the machined surfaces was also analyzed through the scanning electron microscope(SEM).

Chapter: 6 is all about the conclusions of this all research work. This chapter also highlights the drawback of the study and scope for the future work in this area. This chapter is followed by references.

2.1 INTRODUCTION

Since the invention of WEDM machine, several efforts have been made to enhance the machining performance and process steadiness. Process stability is the important factor for converting a material removal process into a convenient machining process. A major quantity of research has explored the various methodologies of achieving the ultimate WEDM goals of optimizing the several process parameters analytically with the whole elimination of the wire breakages thereby additionally also improving the overall machining reliability. The wire electrode is one of the important factors among the various others factors which is contributing well in the overall performance of WEDM. Many researchers have put their efforts towards the progress of wire electrodes for enhancement of WEDM capabilities.

The main section of this chapter focuses on the wire associated factors for improving WEDM performance. Machining speed of WEDM is linked with conductivity of wire electrodes and cryogenic treatment has been proved to be one of the proficient methods to improve the conductivity of the EDM brass wires and relieve stresses in the materials. The literature on cryogenic treatment is also incorporated in this chapter. The detailed literature review over WEDM is presented over here:

2.1.1 PERFORMANCE CHARACTERISTICS OF WEDM PROCESS

Wire electric discharge machining (WEDM) is a process of causing alternating discharge between wire electrode and work piece, through a dielectric fluid. WEDM is an obligatory machining technique used to produce complex two- and three-dimensional shapes through complicated to machine electrical conductive materials [Pandey and Shan, 1980]. The performance measures in the WEDM are cutting speed, surface finish, dimensional deviation and form accuracy. The main machining parameters, which influence the performance of WEDM are; pulse-on time, pulse-off time, wire feed, wire speed, wire tension, servo reference mean voltage, nature of wire and dielectric fluid pressure etc. Numerous studies have been undertaken in the past in order to progress the

performance characteristics, specifically the cutting speed, surface roughness and dimensional deviation etc. The related involvement is discussed below.

Sarkar et al. (2008) investigated modeling and optimization of wire electrical discharge machining(WEDM) of γ -TiAl in the trim cutting operation. A second-order mathematical model, in requisites of machining parameters, was advanced for cutting speed, surface roughness and dimensional deviation using response surface methodology (RSM).

D.K. Aspinwall et al. (2008) investigated work piece surface roughness and integrity after performing WEDM of Ti-6Al-4V and Inconel 718 using smallest amount damage generator technology. Results include 3D topographic maps of work piece surface, micro structural and micro hardness depth profile data. Average recast thickness was <11 mm, several trim passes showing no apparent recast or damage. Similarly, no significant change in workpiece microhardness variation was observed with cracking confined to the recast layer.

Aniza Alias et al. (2012) investigated the control of feed rate on the performance of WEDM on Titanium Ti-Al-4V. Brass wire was engaged as the electrode in this study. The results on kerf width, material removal rate and surface roughness are retrieved. As feed rate increase; MRR also increases till it reaches optimum value. Low machine feed rate gives bigger crater compared to high feed rate and vice versa.

Vikas et al. (2014) presents an idea about the effect of the different input process parameters like the Pulse ON time, Pulse OFF time, Voltage and Discharge Current over the Surface Roughness for an EN41 material. It was found out that the discharge current had a bigger impact over the Surface Roughness value, followed by the Voltage.

Manjaiah M et al. (2014) done investigations of effect of process parameters on the responses such as material removal rate and surface roughness of Ti50Ni40Cu10 SMA machined by WEDM using the Taguchi techniques to acquire optimum machining process parameters. Experimental results exhibit that peak current, pulse on time and servo voltages are major significant factors affecting the MRR and surface finish during machining. Pulse off time and wire feed had no significance on the responses.

Pujari Srinivasa Rao et al. (2014) studied the effect of wire EDM parameters on aluminium alloys as the application of AL is rising in various industries. In this present investigation, the parametric examination of wire EDM parameters was performed by using Taguchi techniques on surface roughness (SR) and material removal rate (MRR).

The rising discharge energy usually increases surface irregularities due to a large amount of melting and resolidification of materials. So the minimum surface roughness is obtained at lower values of peak current and pulse on time.

2.1.2 WIRE ELECTRODES FOR ENHANCING WEDM PERFORMANCE

The broad range of published work relating to wire electrode progress and its performance characteristics has been categorized into diverse sections, namely plain wire electrodes, coated wire electrodes, dispersion annealed wire electrodes, gamma coated electrode wire, composite wire electrodes and porous wire electrodes (Fig. 2.1).

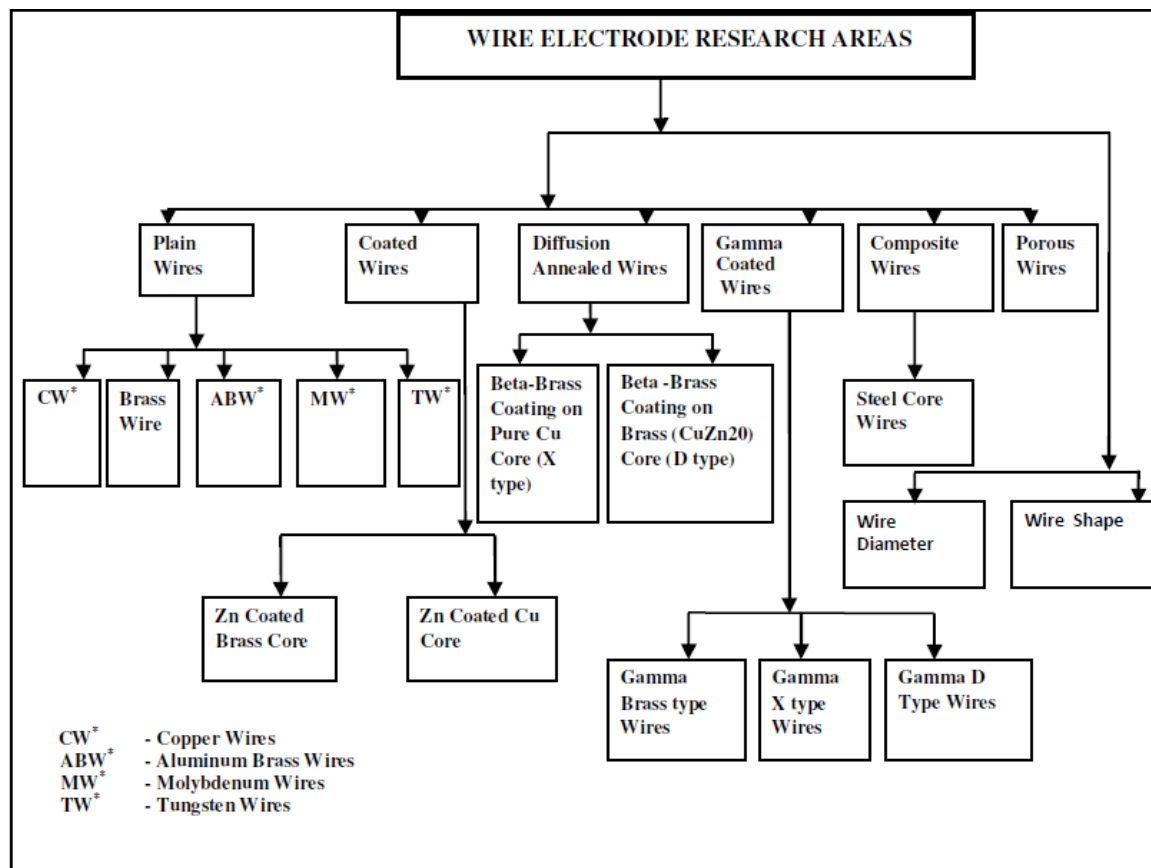


Fig 2.1: Different Types of Wire Electrodes

2.1.2.1 The Plain Wire Electrodes

These wires contain only a single homogeneous element so they are known as plain EDM wire electrode. These wires do not have the coated/composite construction.

2.1.2.1.1 Copper and the Brass Wires

Copper was the initial material first used as electrodes in WEDM applications because of its admirable electrical potential, high elongation and its capability to be simply fashioned

in fine wires. The use of these wires was limited owing to its small inability and mechanical strength to regulate vibrations, which results in slow machining speed, substandard machining precision and predisposition (Aoyama, 2001).

The brass wires shown in Figure 2.2 are the amalgamation of zinc and copper, alloyed together in the assortment of 63 to 65% copper and 35 to 37% zinc (Schacht, 2004a).

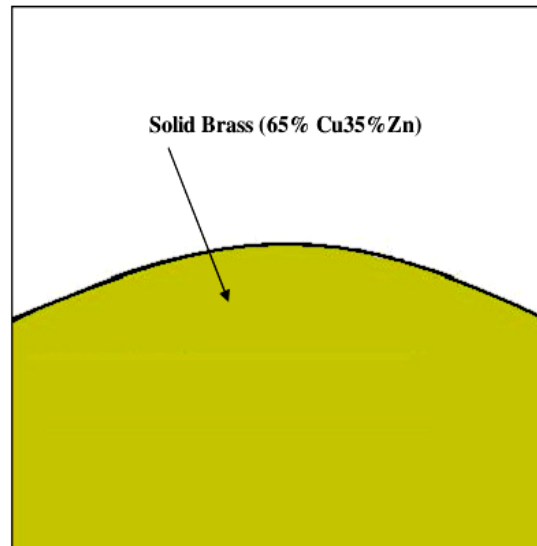


Figure 2.2 Plain Brass Wire Electrode
(Toshiyuki et al., 2005)

2.1.2.1.2 Molybdenum and the Tungsten Wire Electrodes

For lesser diameters, molybdenum or the tungsten wire electrodes are to be utilized because of its elevated tensile strength and weight conveying capacity (Uhlmann and Roehner, 2008). The Moly Wire is very abrasive to power feeds and wire guides, and is often complex to auto thread. The accurateness of the cut face of the work piece can also be enhanced (Gruber and Kunz, 2004, Ezaki, 1991a).

2.1.2.1.3 The Aluminum brass wire electrode

Small proportion additions of aluminum to brass (Fig. 2.3) enhance the tensile strength of wire (near about 1200 N/mm²) exclusive of disturbing the elongation property. These types of wire electrodes are less susceptible to fracture than plain brass wires. These are commonly accessible in brand name names like Somal, TAF, etc. (Kern, 2007b).

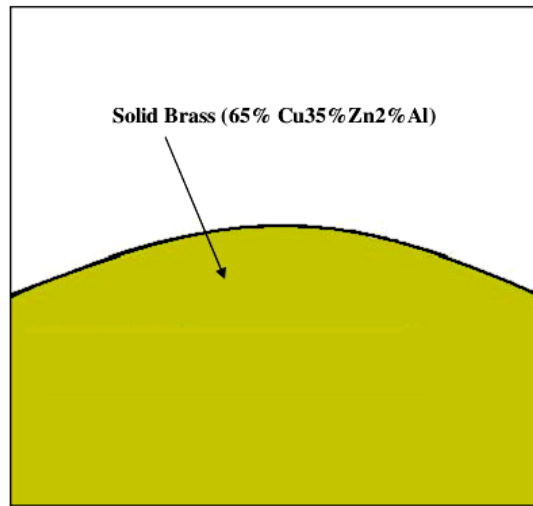


**Figure 2.3 Aluminium Brass Wire Electrode
(Toshiyuki et al., 2005)**

2.1.2.2 Coated Wire Electrodes

Coated wires are formed by plating or hot-dipping re-draw wire (0.9mm) and consequently drawing it to final size. At present, no EDM wires are manufactured by a procedure in which the coating is deposited at finish wire size (Anish et al. 2012)

2.1.2.2.1 Zinc Coated Brass Wire Electrode

This wire consists of a thin (roughly 5 micron) zinc coating over a core which is one of the usual EDM brass alloys. This wire offers a considerable increase in cutting speed over plain brass wires, without any give up in any of the other critical properties. But due to its high cost, uneven concentration of zinc, alter of characteristics of brass wire, creation of dangerous gases, a new technique to coat zinc on the brass was projected (Lee, 2006) to improve the drawback of prior art.

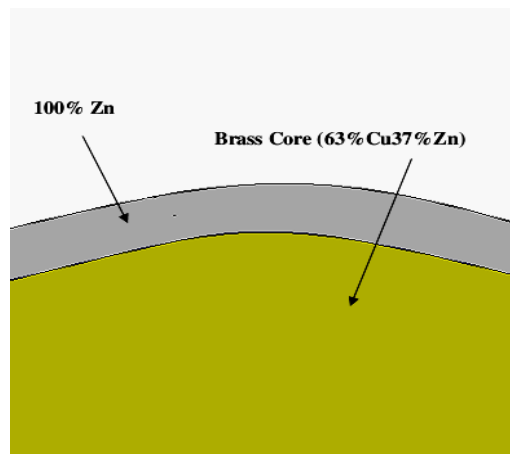


**Figure 2.4 Pure Zinc Coating on Brass
Wire Core (Conves et al., 1981)**

2.1.2.3 Diffusion Annealed Coated Wires

Fleischbach and Hermann (1990) conducted their research to get better the performance of zinc coated brass/copper wires by the process of diffusion annealing of the EDM wires. Copper atoms from brass disseminate into Zn atoms, and Zn atoms diffuse into brass.

2.1.2.3.1 The X -Type Diffusion Annealed Wires

Hermann and Groos (1990) discovered a method of manufacturing a conducting wire electrode, which has a conductive core and coating of structural composition providing superior resistance against the erosive wear. This was the primary diffusion annealed wire and is usually known as SWX, Bronco Cut-X, Beta Cut- X, X-Cut, and other brand names.

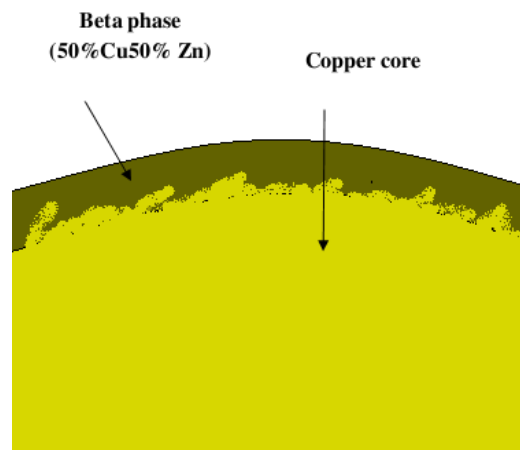


Fig 2.5: X -Type Wire Electrode Conves et al., 1981)

2.1.2.3.2 The D- Type Diffusion Annealed Wires

These types of wires are the further enhancement over X type wires. The Beta brass coated above the copper-alloyed core (20%Zn, 80%Cu). This was the second diffusion annealed wire and is usually known as Cobra Cut-D, D-Kut, and other brand names Its drawback is its high cost. This wire produces significant productivity gains in practically all materials and on many different machines.

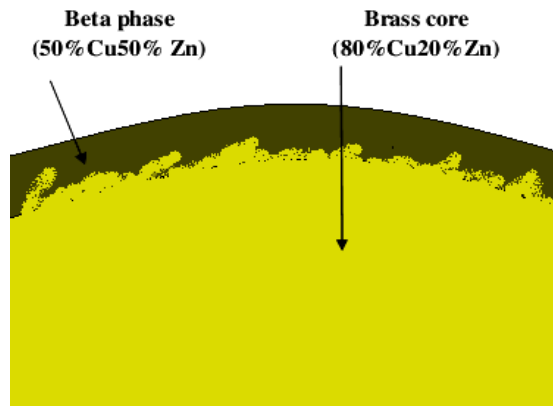


**Figure 2.6 D-Type Diffusion Annealed Wire Electrode
(Tomalin, 2007b)**

2.1.2.4 Gamma-Coated Wires

The continual development for getting higher cutting speed in Wire Electric Discharge machining(WEDM) has led to the advancement of gamma-coated wires (Fig. 2.7). It was investigated (Briffod, 1993) that diffusion-annealed beta phase brass consist of zinc content in the range 45%-50% and has high melting point, thereby providing outstanding firmness. These wires have the potential of reducing cycle time by lowering the expenditure of rough cuts via increased removal rate.

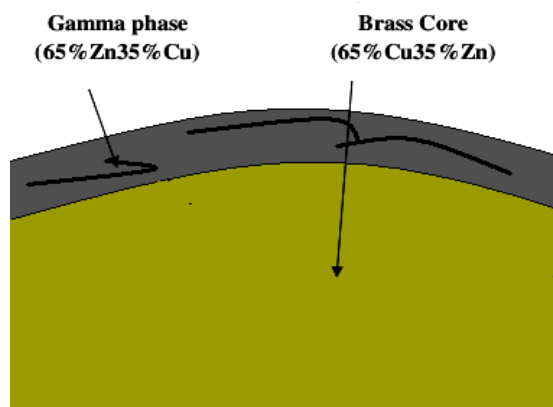


**Figure 2.7 Gamma Brass Wire Electrode
(Barthel et al., 1998)**

2.1.2.4.1 Gamma-X and Gamma-D Type Wires

Inventions carried out by different inventors (Tomalin,1999; Bariffod, 1993; Baumann and Barthel, 2002; Nakai et al., 2001b; Gonnissen and Vanvooren, 2001) also tried to

cover the conductive core with a coating of multiple fine layers. According to the embodiments of the invention by Barthel and Nuser (2003), the wire electrode core prepared of copper (X-type wires) or copper alloy (D-type wires) are first diffusion heat treated for the creation of beta phase and then stabilization treating steps are performed in order to construct the outer coating of gamma phase (Figure 2.8 and Figure 2.9).

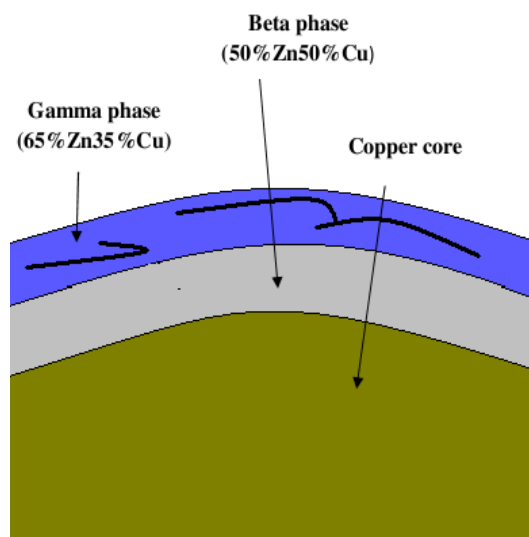


Figure 2.8 Gamma X-Type Wire Electrode (Barthel and Nuser, 2003)

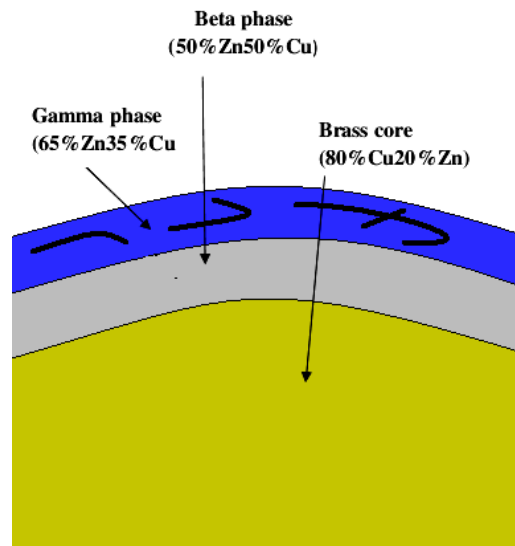


Figure 2.9 Gamma-D Wire Electrode (Barthel and Nuser, 2003)

These wires are commercially known as Gamma-X, Gamma-D or Versacut H. These wire electrodes execute superior on aerospace alloys under good flushing environment.

2.1.2.5 Composite Wires (Copper Clad Steel Core)

Composite wires combine conventional EDM wire alloys with non-EDM materials to generate EDM wires with distinctive properties for specialty applications in giant work pieces, interruptible cuts and for poor flushing conditions.

Tominaga et al., (1987) in their research disclosed coated wires having a copper clad steel core and a layer of beta brass that provides superior conductivity and superior machining accuracy.

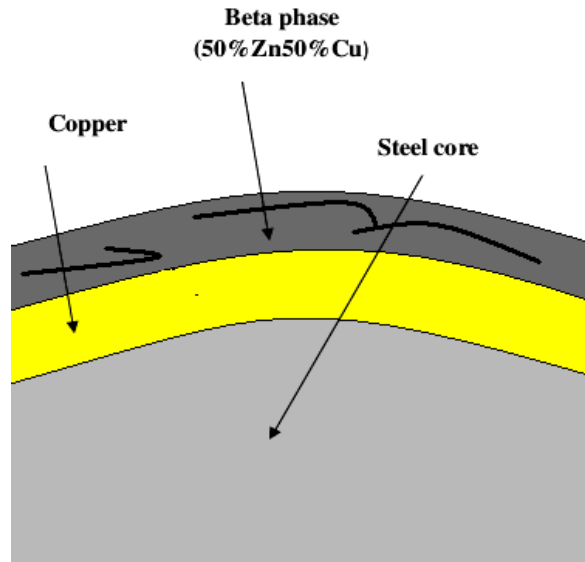


Figure 2.10 Composite Wire Electrode (Kern, 2007a)

These steel core wires (Fig. 2.10) are generally known as compeed, microcut, macrocut (Kern, 2007c).

2.1.2.6 Porous Electrode Wire

Tomalin (2007a) disclosed in his prior art that diffusion annealed wire electrodes may be porous, infiltrated with graphite to further enhance its discharge properties. Porous nature of the wire is expected to improve flushability during EDM, providing spaces to eliminate particles resulting from the WEDM. The Hansen and Anderko (1958) identified elipson phase brass as 84Zn/16Cu.

2.2 CRYOGENIC TREATMENT

The revolutionary work in low temperature by the British chemists Michael Faraday and Sir Humphry Davy between 1823 and 1845 arranged the way for the development of cryogenics. The combination of the reduced temperature and increased pressure caused the evolved gases to liquefy. The temperature of about -110°C was successfully reached by evaporating the solid carbon dioxide mixed with low pressure (Bryson, 1999). The liquid oxygen was produced by French physicist Louis Paul Cailletet and the Swiss Scientist Raoul Pierre. The first liquefied hydrogen was produced by British chemist Sir James Dewar (Collins, 1965).

Shallow cryogenic treatment refers to the treatment of materials at very less temperatures, generally at around -110°C and deep cryogenic treatment refers to the treatment of materials at temperature around -190°C . The brief literature of the effect of cryogenic treatment is given as:

Tarr and Rhee (1977) observed that when the alloy is subjected to the liquid nitrogen temperature, the thermal conductivity is enhanced by 3-4% without affecting the hardness from re-aging.

Gillin (1995) in his prior art disclosed the effect of cryogenic treatment on electrical contacts. If an electrical contact is exposed to a low temperature for a selected period of time, it results in an extended useful life of the contact. The cryogenically treated electrical contact exhibit superior abrasion resistance and adhesion to backing, than non treated contacts.

Mohan Lal et al. (2001) observed that cryogenic treatment is not just surface treatment, but it affects the entire cross-section of the materials.

Kamody (2001) describes the effect of cryogenic treatment to minimize the instability effects of workpieces, which results in the regulation and compensation of wire burning action.

Reitz and Pandary (2001) reported noticeable effect of cryogenically treated steels and other materials, like copper alloy, aluminum alloys, titanium, cemented carbides, ceramics and some polymers. The improved behavior in service performance is due to stress relieving in microstructure and homogeneous lattices.

Zhisheng et al. (2003) investigated the effect of deep cryogenic treatment on spot welding electrodes. It was observed that deep cryogenic treatment causes Cr and Zr atoms to disperse and makes the grains smaller, more uniform and compact than non cryogenic treated electrodes.

Bensely et al. (2005) acknowledged the improvement of wear resistance of steel with deep and shallow cryogenic treatment as compared to conventional heat treatment.

Molinari (2001) The cryogenic treatment has been found to increase the tool life of high speed steels from 65% to 343% depending on the cutting conditions used in the process.

Jatinder et al (2013) investigated the the effect of deep and shallow cryogenic treated wire electrodes on the material removal rate (MRR) and the surface roughness (SR) of an EN-31 steel machined by WEDM. All the three process parameters, namely Type of wire, pulse width and wire tension significantly affect the MRR, SR in WEDM. Deep and shallow cryogenic treated wire electrodes appreciably enhance the MRR. Scanning

electron microscope (SEM) photographs confirm that cryogenically treated wires gives smoother surface than untreated wire electrode. EDS analysis revealed that cu and zn elements from brass wire electrode were deposited on the machined surface of workpiece.

2.3 GAPS IDENTIFIED IN THE LITERATURE REVIEW

Literature review in this chapter reveals that a substantial amount of work on different aspects of machining with WEDM has been reported. On the thorough examination of the published work on the WEDM with high performance and standard wire electrodes, the following gaps in the literature have been identified:

1. The high performance wires appreciably increase WEDM productivity over plain brass wires but primary limitations of these wires are high cost, damage to scrap chopper, straightness issues and environmental hazards. There is very limited literature existing on the study of these aspects.
2. Many researchers have studied the effect of cryogenic treatment on materials like D2, D3 etc, but very few research studies are available which mention the cryogenic treatment of high speed steels like M42, M35 etc.
3. Technology charts or operator reference manuals are not available for effective machining of HSS M42 using WEDM. So, there is a need to generate optimal sets of process parameters satisfying a number of performance measures such as machining rate, surface roughness, dimensional deviation etc.
4. Most of the researchers have carried out multi objective optimization of objective functions using traditional optimization techniques such as Taguchi method, min-max method, weighted method etc. Multi objective optimization of process parameters is needed to be done using some evolutionary optimization techniques such as response surface methodology (RSM), as literature survey reports a lot about limitations of traditional optimization techniques.
5. Very limited work has been reported on evaluation of the surface integrity of HSS after machining. The novelty of present research work is the investigation of the surface integrity of the machined samples of M42 and wire surface topography, analyzed through scanning electron microscope (SEM). The influence of process conditions on surface topography, recast layer, heat affected zone, formation of micro-cracks and debris analysis was considered in the present study.

6. No significant literature has been found relating to optimization of surface integrity in terms of number of micro-cracks, length of micro-cracks, surface crack density and recast layer thickness after processing with WEDM.

In the light of the above mentioned gaps, the present research was aimed to discover the possibilities for the improvement in the WEDM process efficiency and the surface finish of WEDMed processed material with cryogenic treated brass wire electrode. The effect of cryogenic treatment on the wire electrode is imperative to be investigated. Following broad areas were identified for the present research work.

2.4 Properties of Cryogenic Treated Wires

The conductivity of brass wire electrode in WEDM has a tough effect on the machining mechanism, process performance and overall surface integrity of the processed surface. Along with traditional parameters of the WEDM, the selection of wire electrodes of different conductivities to achieve best possible performance in terms of machining efficiency and surface finish is difficult to study. Therefore systematic study of properties of the non-cryogenated treated and cryogenic treated brass wire electrodes and for the optimal setting of process parameters with diverse wire electrodes seem to be an interesting and challenging area of research.

2.5 Performance Improvement

The study of the WEDM indicates that if target is to achieve high cutting speed then the surface finish will be less and there will be high wear of wire electrode. Therefore, improvement in cutting speed, SR, and dimensional deviation are normally considered to be the response characteristics. It is pertinent to mention here that Cutting Speed, Surface Roughness and Dimensional Deviation are also associated with the conductivity of wire electrode.

It is planned to treat the wire electrode with cryogenic treatment at the different cryogenic temperatures like shallow cryogenic temperatures(-110°C). Detailed experimentation is projected to study the effect of cryogenic treatment to wire electrodes used in WEDM.

2.6 Optimization of Process Parameters

For making any process cost efficient, process optimization is necessary. Regular monitoring of process is necessary to reduce manufacturing imperfections in the process/products.

The treatment of the wire electrode with cryogenic treatment may manipulate other parameters such as pulse width, time between the two pulses, wire tension, servo reference mean voltage etc. of WEDM. Therefore reassessment of the performance of WEDM in combination with and without the cryogenically treated wire electrodes and their various characteristics are required. An experimental work is projected to study the effect of various process parameters of the WEDM with the treated and untreated wire electrodes on its performance characteristics.

2.7 OBJECTIVE OF THE STUDY

To investigate effect of the process parameters on the performance characteristics of WEDM with non-treated and cryogenic treated wire electrode.

2.8 OVERALL METHODOLOGY

1. An experimental setup for experimentation on CNC wire cut electrical discharge machine has been developed.
2. The range and levels of parameters of WEDM for non-treated and cryogenically treated brass wire were decided.
3. The effect of the cryogenic treatment on the brass wire electrode was studied.
4. The effect of non-treated and cryogenated treated brass wire on HSS M42 was studied by performing experiments using BBD.
5. An extensive experimentation was carried out based on experimental design, such as BBD to develop parametric relationships for WEDM for studying the effect of cryogenic treatment the on brass wire electrode.
6. Surface characteristics of WEDMed surfaces of the work pieces and wire electrodes were examined with the help of the Scanning Electron Microscopy (SEM).
7. Process parameters were optimized by using the multi-objective techniques.

CHAPTER 3

DESIGN OF STUDY

3.1 INTRODUCTION

WEDM is a speculative process and a large number of control factors influence the process in a intricate way. Any adjustment even in a single parameter may produce unexpected results leading to loss of productivity, decline in surface quality or both apart from the unexpectable results on the material properties such as change in micro hardness and microstructure. The solution of this deceit in the process analysis to generate optimal machining parameters which may engage detailed experimentation and subsequent analysis of results. In investigational studies, input variables called as control factors are changed and their effect on output performance measures (responses) are observed. Each control factor can take numerous values during the course of experimentation work. Such values of control factors are called levels or treatments. An experiment (also called trial or run) is a arrangement of parameters at different levels whose effect on the output is of primary concern.

For the conduct of experiments, a scientific approach is obligatory to plan the experiments, so as to give equal importance to all control factors in addition to preserving toughness of the process. A well planned and executed set of experiments is of main importance for deriving apparent and accurate conclusions from the experimental observations.

Keeping in view above, Sir Ronald A. Fisher formulates factorial experiment designs, which focus on simultaneous change in a number of factors at a time [Montgomery, 2002]. A very useful strategy named as design of experiments was established. Design of experiments (DOE) is defined as, “A compilation of mathematical and statistical technique that are supportive for modeling and investigation of problems in which a response of interest is inclined by several variables and purpose is to reform this response” [Montgomery, 2002]. Design of experiments offers a lot of advantages that are as follows [Alder et al., 1975; Peterson, 1985; Ferreira et al., 2007]:

- (i). The employ of design of experiments offers advantages such as decline in the number of experiments that require to be performed, which leads to proficient use of resources and time.

- (ii). Estimation of the experimental error aroused in the phase of experimentation.
- (iii). It allows evaluation of the relevance and statistical significance of a factor and is able to estimate the interaction effects among the factors as well.
- (iv). Experimental modelling of output response in terms of process parameters can be done.
- (v). An optimal combination of process parameters generating maximum or minimum yield criteria can be obtained with a flexibility to set the comparative priorities among the yield criteria or response functions.

The research on experimentation strategies has been further investigated to full factorial designs, fractional factorial designs [Peterson, 1985], Response Surface methodology (RSM) [Myers, 1990; Montgomery, 2002] and Taguchi methodology by obtaining maximum from the concepts of DOE. The Literature reveals that, generally, one factor at a time approach is used for carrying out of selection experiments or preliminary investigation of the process. For detailed experimentation and analysis Response Surface methodology or Taguchi methodology is preferred. Taguchi's methodology for design of experiments is extensively reported in the literature [Mahapatra and Patnaik, 2006; Kuriokase and Shagunmun, 2005], but it has certain inherent weaknesses that are as follows [Myers, 2002; Box, 1988; Hunter, 1989] :

- (i). Taguchi's methodology makes use of signal to noise ratios (S/N ratios) that sum up the observations and provide information about mean and standard deviation of one measure in analyzing data from a tough design view point. The S/N ratios and loss function baffle location (mean) and dispersion (variance) effects. In other words, the signal to noise ratio and loss function enclose information concerning both mean and the variability and the particular effect of variables on these two measures cannot be assessed.
- (ii). In Taguchi's methodology, interaction effects are assumed to be negligible unless they are explicitly recognized. In addition, the generally accepted method of creating these designs does not always achieve optimum design resolution to mitigate the problem of effect confounding.
- (iii). This methodology lacks in building mathematical models that describe, how the performance changes as a function of control and noise variables. Such mathematical models not only provide a basis for developing an understanding of

the phenomenon of interest, but are also required for suggesting directions for further improvement.

- (iv). The results obtained using Taguchi's method are not truly optimal as in most cases optimization techniques are not employed. In addition sequential nature of experimentation is not pursued.
- (v). Simultaneous optimization of more than one objective functions cannot be carried out; unless some another technique such as Grey relation analysis is employed on the already obtained results.

Considering these limitations of Taguchi's method, the present study utilizes RSM for designing the experiments and carrying out detailed investigation on WEDM of M42 High Speed Steel(HSS). The following section briefly describes RSM.

3.2 RESPONSE SURFACE METHODOLOGY

RSM is a arrangement of mathematical and statistical techniques used in experimental study of relationships and optimization where numerous independent variables or factors manipulate a dependent variable or response. It was developed by Box and Wilson in 1951 while working on a chemical exploration, based on the pioneering works in association with agricultural experimentation [Box 1952; Box and Hunter, 1957]. RSM also quantifies the relationship between controllable input parameters and obtained response surfaces [Kwak, 2005]. This methodology has been effectively used in agricultural and chemical fields and also in production engineering works as in turning, milling, grinding, welding, extrusion and press working, etc. The design procedure of RSM is as follows [Gunaraj and Murugan 1999]:

- (i). Designing of a chain of experiments for adequate and trustworthy measurement of the response of interest.
- (ii). Making a mathematical model of the second order response surface with the best fittings.
- (iii). Finding the finest set of experimental parameters that produce a maximum or minimum value of response.
- (iv). Representing the direct and collective effects of process parameters through two and three dimensional plots.

If all variables are assumed to be calculable, the response surface can be expressed as follows:

$$y = f(x_1, x_2, x_3, \dots, x_n) \quad \dots (3.1)$$

Where

$$\begin{aligned} y &= \text{output response} \\ x_i &= i^{\text{th}} \text{ independent variable (Control factor)} \end{aligned}$$

The aim is to optimize the response variable y . In RSM, dependant variable (response variable) is viewed as a surface to which a mathematical model is fitted. Usually a two factor interaction or second-order surface is utilized in RSM that is given by following equations [Kwak, 2005; Gunaraj and Murugan, 1999].

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i < j} \beta_{ij} x_i x_j + \varepsilon \quad \dots (3.2)$$

where

$$\begin{aligned} y &= \text{output response} \\ x_i &= i^{\text{th}} \text{ control factor} \\ \beta &= \text{regression coefficient} \\ \varepsilon &= \text{random error} \end{aligned}$$

Regression coefficients (β) are occasionally called partial regression coefficients as β_i measures the expected change in y per unit change in x_i when x_j are held constant. The assumed surface y contains linear, squared and cross product terms of the variables x_i .

3.2.1 Estimation of Regression Coefficients

The method of least squares is typically used to calculate approximately the regression coefficients in a multiple linear or quadratic regression model [Gunaraj and Murugan, 1999]. In general Equation (3.2) can be written in matrix form.

$$y = X \beta + \varepsilon \quad \dots (3.3)$$

Where y is defined to be a matrix of measured values, X to be a matrix of independent variables. The matrixes β and ε consist of coefficients and errors, respectively.

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \quad X = \begin{bmatrix} 1 & X_{11} & X_{21} & \cdot & X_{1k} \\ 1 & X_{21} & X_{22} & \cdot & X_{2k} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ 1 & X_{n1} & X_{n2} & \cdot & X_{nk} \end{bmatrix} \quad \beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \cdot \\ \cdot \\ \beta_k \end{bmatrix} \quad \varepsilon = \begin{bmatrix} \varepsilon_0 \\ \varepsilon_1 \\ \cdot \\ \cdot \\ \varepsilon_n \end{bmatrix}$$

In general, y is an $n \times 1$ vector of observations, X is an $n \times k$ matrix of levels of independent variables, β is a $k \times 1$ vector of regression coefficients and ε is an $n \times 1$ vector of random errors. The goal is to find the vector of least square estimators, b that minimizes L that is as follows:

$$\begin{aligned} L &= \sum_{i=1}^n \varepsilon_i^2 = \varepsilon' \varepsilon = (y - X\beta)'(y - X\beta) \\ &= y'y - \beta'X'y - y'X\beta + \beta'X'X\beta \\ &= y'y - 2\beta'X'y + \beta'X'X \end{aligned} \quad \dots (3.4)$$

Since $\beta'X'y$ is a 1×1 matrix, or scalar, and its transpose $(\beta'X'y)' = y'X\beta$ is the same scalar. The least square estimators must satisfy

$$\begin{aligned} \left. \frac{\partial L}{\partial \beta} \right|_b &= -2X'y + 2X'Xb = 0 \\ X'Xb &= X'y \end{aligned} \quad \dots (3.5)$$

Equation 3.5 is set of normal equations in matrix form. Multiply both sides of this by inverse of $X'X$. Thus, least square estimator of β is [Kwak, 2005; Gunaraj and Murugan 1999]:

$$b = (X'X)^{-1}X'y \quad \dots (3.6)$$

The fitted regression model is

$$\hat{y} = Xb \quad \dots (3.7)$$

Where $\hat{y}$ = estimate of y

3.2.2 Model Adequacy Checking Tests

Model adequacy checking is necessary to (a) Examine the fitted model to make sure that it provides an adequate approximation to the true system and (b) to verify that none of the least square assumptions are despoiled. The various techniques used for it are described below [Myers, 2002].

3.2.2.1 Sum of Squares of Residuals Technique

The difference between observation y_i and fitted value $\hat{y}$ is called residual (e). The $n \times 1$ vector of residuals is denoted by

$$e = y - \hat{y} \quad \dots (3.8)$$

The method of least square produces an unbiased estimator of the parameter β in the multiple regression models. The important parameter is the sum of squares of the residuals (SS_E)

$$SS_E = \sum_{i=1}^n (y_i - \hat{y})^2 = \sum_{i=1}^n (e_i)^2 = e'e \quad \dots (3.9)$$

From (3.7 and 3.8) substituting $e = y - \hat{y} = y - Xb$,

$$\begin{aligned} SS_E &= (y - Xb)'(y - Xb) \\ &= y'y - b'X'y \end{aligned} \quad \dots (3.10)$$

The above equation is called residual sum of squares with $n-k-1$ degrees of freedom.

Total sum of squares (SS_T) is given by following equation with $n-1$ degrees of freedom

$$SS_T = y'y - \left(\sum_{i=1}^n y_i \right)^2 / n$$

It is necessary to test for significance of the model. This test procedure involves partitioning the total sum of squares into sum of squares due to model (regression) and sum of squares due to error [Myers, 2002].

$$\begin{aligned} SS_T &= SS_R + SS_E \\ SS_R &= b'X'y - \left(\sum_{i=1}^n y_i \right)^2 / n \text{ with } k \text{ degrees of freedom} \end{aligned} \quad \dots (3.11)$$

3.2.2.2 Test for Significance of Regression

F Statistics is a test for comparing model variance with residual (error) variance. It is the ratio of mean square of regression (MS_R) to the mean square of error (MS_E).

Where

$$\begin{aligned} MS_R &= \frac{SS_R}{k} \\ MS_E &= \frac{SS_E}{n - k - 1} \end{aligned}$$

If model F value exceeds $F_{\alpha, k, n-k-1}$, then the model is considered valid. Alternatively, p-value approach to hypothesis testing can be utilized, according to which if p-value of the F statistics of the model is lower than the confidence interval (α), the model is considered applicable.

R^2 is a measure of amount of decline in the variability of y obtained by using the regressor variables $x_1, x_2, \dots, x_n$ in the model and is defined by ratio of sum of squares due to regression to the total sum of squares ($\frac{SS_R}{SS_T}$). The domain for $R^2 = 0$ to 1. A larger value of R^2 does not necessarily entail that regression model is good one. Adding a variable to the model will always increase R^2 , in spite of whether the additional variable is statistically significant or not. Thus, it is preferred to use an adjusted R^2 statistics that is defined as follows:

$$R_{adj}^2 = 1 - \frac{SS_E / (n - k)}{SS_T / (n - 1)}$$

Adjusted R^2 is a measure of the amount of variation about the mean explained by the model, adjusted for the number of terms in the model. The adjusted R-square decreases as the number of terms in the model increases, if those supplementary terms don't add value to the model.

Adequate Precision is a term that measures signal to noise ratios. It compares the range of the predicted values at the design points to the average prediction error. Ratios greater than 4 indicate adequate model discrimination.

3.2.2.3 Test for Lack of Fit

It is normally useful to obtain two or more observations (replicates) on the response at the similar settings of independent variables. Thus, sum of the square for residuals can be dismembered into two more parcels: the sum of the square due to pure error (SS_{PE}) and the sum of the square due the lack of fit (SS_{LOF}), as shown below:

$$SS_{RES} = SS_{PE} + SS_{LOF}$$

$$SS_{PE} = \sum_{i=1}^m \sum_{j=1}^{n_i} (y_{ij} - \bar{y}_i)^2$$

$$SS_{LOF} = \sum_{i=1}^m n_i (\bar{y}_i - \hat{y}_i)^2$$

$$MS_{PE} = \frac{SS_{PE}}{n_i - 1}$$

$$MS_{LOF} = \frac{SS_{LOF}}{m - k}$$

Where

y_{ij}	=	j^{th} observation on the response at y_i
n_i	=	number of observations at i^{th} level
m	=	levels of x_i
$n_i - 1$	=	degrees of freedom associated with SS_{PE}
$m - k$	=	degrees of freedom associated with SS_{LOF}

Another way to estimate the model is the *lack of fit test*. If the mathematical model is well fitted to the experimental data, MS_{LOF} will reflect only the random errors natural to the system. Additionally, MS_{PE} is also an approximate of these random errors and it is supposed that these two values are not statistically different

$$\frac{MS_{LOF}}{MS_{PE}} \approx F_{(dlof, dpe)}$$

where, $dlof$ and dpe are the degree of freedom allied with the lack of fit and the pure error respectively. If this ratio is higher than tabulated value of F , it is concluded that there is evidence of a lack of fit and that the model desires to be improved

3.3 RESIDUAL ANALYSIS

The residuals from least square fit to play an important role in judging the model adequacy. A check on the regularity assumption may be made by constructing a normal probability plot of residuals. If the residuals plot is approximately along a straight line, then the normality assumption is fulfilled. Various types of residuals are evaluated for judging the capability of the model, that are as follows [Myers, 2002; Montgomery, 2002]:

3.3.1 Standardized and Studentized Residuals

Scaled residuals such as standardized and studentized residuals express more information than ordinary least square residuals.

$$\text{Standardized residuals } d_i = \frac{e_i}{\hat{\sigma}} \quad i= 1, 2, \dots, n$$

$$\text{Where } \hat{\sigma} = \sqrt{MS_E}$$

These standardized residuals have mean zero and approximately unit variance and are helpful in looking out for outliers. Most of the standardized residuals should lie in the

interval $-3 \leq d_i \leq 3$. Any observation with a studentized residual exterior this limit may represent something as simple as data recording error or something of more serious concern. The studentized residual is the number of standard deviations that divide the actual and predicted response values. It is calculated by the ratio of residual to the estimated standard deviation of the residual.

$$\text{Studentized residual} = \frac{e_i}{\sqrt{\hat{\sigma}^2(1-h_{ii})}}$$

Where

h_{ii} = measure of location of the i^{th} point in x space.

The studentized residuals have constant variance equal to 1 regardless of the location of x_i , when the form of the model is accurate.

3.3.2 Prediction Error Sum of Squares Residuals

The prediction error sum of squares (PRESS) provide a helpful residual scaling. To calculate PRESS, i^{th} observation is selected and the regression model is fitted to remaining $n-1$ observations. The equation developed so is utilized to forecast the withheld observation y_i . Denoting this predicted value by $\hat{y}_{(i)}$, now find the prediction error for point i as $e_i = y_i - \hat{y}_{(i)}$. This prediction error is called i^{th} PRESS residual. This procedure is continual for each observation. Then PRESS statistics is defined as sum of squares of the n such PRESS residuals in the following manner

$$PRESS = \sum_{i=1}^n e_i^2 = \sum_{i=1}^n (y_i - \hat{y}_{(i)})^2$$

PRESS is used to compute an approximate R^2 for prediction

$$R^2_{\text{prediction}} = 1 - \frac{PRESS}{SS_T}$$

$R^2_{\text{prediction}}$ Indicate predictability of the regression model. Within 95% confidence interval, usually it is enviable to have $0.95 \leq R^2_{\text{prediction}} \leq 1$. It means that it is projected from the model to explain most the variability arising in predicting new observations.

3.4 ANALYSIS OF VARIANCE

Analysis of variance (ANOVA) is a method for analyzing experimental data in which one or more response (or dependent) variables are calculated under various conditions identified by one or more categorization variables. To accomplish this, Sum of squares due to error (SS_E), Sum of squares due to regression (SS_R) and Total Sum of squares (SS_T) are utilized. The (SS_T) is divided into following four parts as shown in Table 3.1 to ascertain contribution of first order terms, second order terms, lack of fit element to measure the deviations of the response from the fitted surface and assessment of the experimental error from center runs [Pecas and Henriques, 2003].

Table 3.1: Analysis of variance using multiple regressions [Marcos et al., 2008]

Variation Source	Sum of Squares (SS)	Degrees of Freedom	Mean Square (MS)
Regression	$SS_R = \sum_{i=1}^m \sum_{j=1}^{n_i} (\hat{y}_i - \bar{y})^2$	$p - 1$	$MS_R = \frac{SS_R}{p - 1}$
Residuals	$SS_{residual} = \sum_{i=1}^m \sum_{j=1}^{n_i} (y_{ij} - \hat{y}_i)^2$	$n - p$	$MS_{residual} = \frac{SS_{residual}}{n - p}$
Lack of fit	$SS_{LOF} = \sum_{i=1}^m \sum_{j=1}^{n_i} (\hat{y}_i - \bar{y}_i)^2$	$m - p$	$MS_{LOF} = \frac{SS_{LOF}}{m - p}$
Pure error	$SS_{PE} = \sum_{i=1}^m \sum_{j=1}^{n_i} (y_{ij} - \bar{y}_i)^2$	$n - m$	$MS_{PE} = \frac{SS_{PE}}{n - m}$
Total	$SS_T = \sum_{i=1}^m \sum_{j=1}^{n_i} (y_{ij} - \bar{y})^2$	$n - 1$	

Where,

- n = number of observation
- m = total number of level in the design
- p = number of parameters of model
- $\bar{y}$ = overall mean
- $\hat{y}_i$ = estimated value by the model for the level i ;
- y_{ij} = replicates performed in each individual levels;

$\bar{y}_i$ = mean of replicates performed in the same set of experimental conditions.

Based upon results obtained from ANOVA, mathematical models consists of significant terms of individual and interaction effects are built for responses of interest.

3.5 BOX- BEHNKEN DESIGNS

BBDs are very popular designs for fitting quadratic response surfaces. BBDs are notable in that, each factor is restricted to 3 levels, just enough to allow for fitting a quadratic term in each factor. Another feature is that, each run other than the center runs has at least one factor set to zero in scaled units. This means that there are no runs where every factor is at one of its extreme values.

A BBD has group of runs, where for each run in the group, only a certain number of factors change. For this group of runs, all the other factors are set at zero in scaled units. The identity of the factors, that vary in each group of runs changes from one group to the next, e.g. in the first group of runs factors x_1 and x_2 might be varied; but in the next group of runs x_3 and x_4 might be the variable factors.

The complete pattern of these changes is described by a balanced incomplete block design. These designs have the property that, every treatment occurs the same number of times and every treatment occurs in a block with every other treatment the same number of times. In BBDs, the “treatments” are the varying factors in a group.

These designs do not run tests at the extreme of every factor. BBD designs are more properly thought of as design on a sphere, rather than design on a cube.

BBDs are rotatable or nearly rotatable, based on 3 level incomplete factorial design [Box and Behenken, 1960]. A design is rotatable, if the variance of the predicted response at any point x , depends on the distance (not direction) of x from its center point. A design with this property can be rotated around its center point without changing the prediction variance at x . Rotatability is a desirable property of a response surface design (i.e. quadratic model design).

BBDs do not contain an embedded factorial or fractional factorial design. For BBDs, the design points fall at combinations of high and low factor level and their mid points.

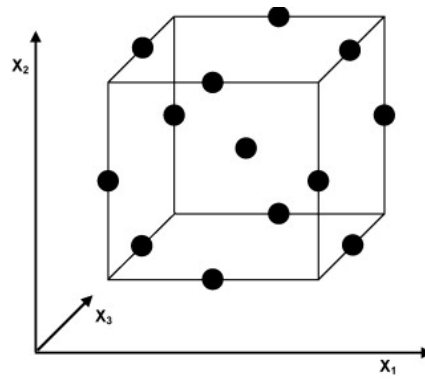


Figure 3.1 BBD represented as a cube [Souza et al., 2005]

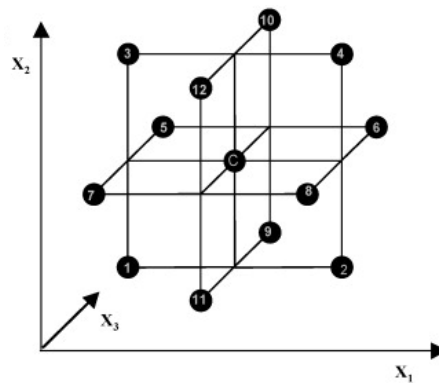


Figure 3.2 Representation of Box Behnken Design(BBD) as 3 Interlocking 2^2 factorial experiments [Souza et al., 2005]

Table 3.2 Comparative study CCD, Full factorial design and BBD of on the basis of number of experiments

No. of Factors	Number of Experiments		
	Central Composite Design(CCD)	Full Factorial Design(FFD)	Box -Behnken Design(BBD)
2	13	9	11
3	20	27	15
4	30	81	27
5	50	243	46
6	86	729	54
7	152	2187	62

CHAPTER 4

EXPERIMENTATION

4.1 MACHINE TOOL

The experiments were carried out on a wire-cut EDM machine (ELEKTRA ECOCUT) of Electronica Machine Tools Ltd. installed at Maharishi Markandeshawar University(MMU) in Mechanical Engineering Department, Mullana Ambala, Haryana, India. The WEDM machine tool (Figure 4.1) has the following specifications:

Table 4.1: WEDM machine tool specifications

Electrical Specifications		
1.	Input power supply	3 Phase, AC 415 V, 50 Hz
2.	Connected load	15 KVA
3.	Average power consumption	6 to 7 KVA
4.	Overload protection	With SIEMENS contractor and 3 phases thermal overload relay.
Mechanical Specifications		
1.	Table size	600 mm ×440 mm
2.	Maximum work piece size	550 mm×350 mm×200 mm
3.	Maximum work piece weight	200 kg
4.	Main table traverse (X×Y)	300 mm× 200 mm
5.	Auxiliary table traverse (U×V)	± 11 mm × ± 11 mm
6.	Vertical table traverse (Z)	210 mm
7.	Main table feed rate	900 mm/min
8.	Resolution	0.0005 mm
9.	Maximum taper cutting angle	± 3mm / 5 mm
10.	Control of axis	X, Y, U, V, Z simultaneous / independent
11.	Wire electrode	0.25 mm (Standard) 0.20 mm, 0.15 mm (Optional)

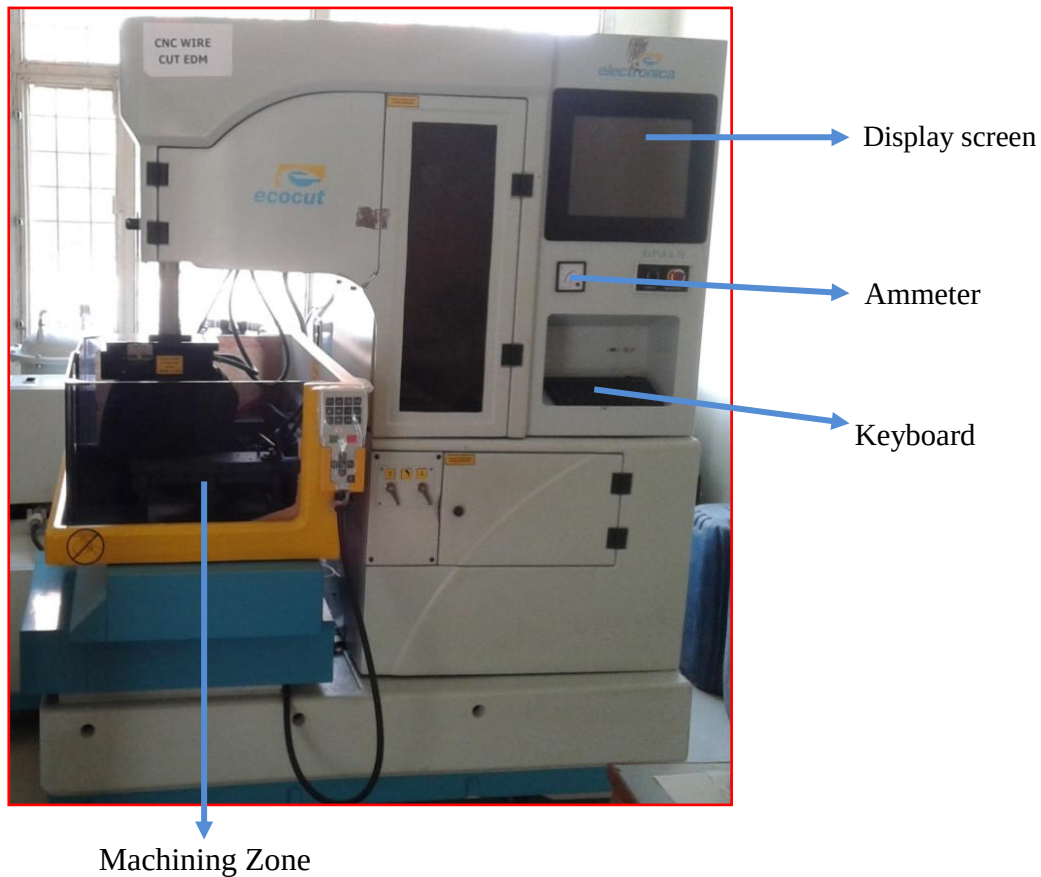


Figure 4.1: Pictorial View of WEDM Machine Tool(Source: Mech.Engg. Deptt, MMEC,Mullana,Ambala)

4.2 SPECIFICATIONS OF WORK PIECE MATERIAL AND MACHINE

M42(High Speed Steel) required for experimentation was procured from the Lalson Tools Corporation, Patiala, India. The M42 high speed steel(HSS) plate of 100mm x 80mm x 12mm size has been utilized as a work piece material for the present experiment tests. M42 super high speed steel is a finest cobalt high speed steel with a chemical composition intended for high hardness and better hot hardness. These properties make the steel an outstanding option for machining high-strength and pre-hardened steels, high-hardened alloys, and the difficult-to-machine, nonferrous super alloys used in the aerospace, oil, and power generation industries.

M42 exhibits brilliant wear resistance by virtue of elevated heat-treated hardness (68 to 70 HRC), and the high cobalt content impart the hot hardness. As such, the cutting edges on tools finished from M42 super high speed steel(HSS) stay sharp and hard in heavy-duty and high-production cutting application.

APPLICATIONS: Twist drills, milling cutters, taps, reamers, broaches, saws, knives, and thread rolling dies.

Table 4.2 Shows chemical composition of M42

Element	C	Si	Cr	W	Mo	V	Co
Weight%	1.08	0.45	3.85	1.50	9.50	1.20	8.00

4.2.1 Preparation of sample work pieces

The M42 high speed steel plate of dimension 100mm x 80mm x 12mm size is mounted on the WEDM (ELECTRONICA ECOCUT) machine tool (Figure 4.1) and sample workpieces of 10 mmx10 mmx12 mm size are cut. The near by view of the HSS M42 plate used for cutting the specimens is shown mounted on the WEDM machine (Figure 4.2).

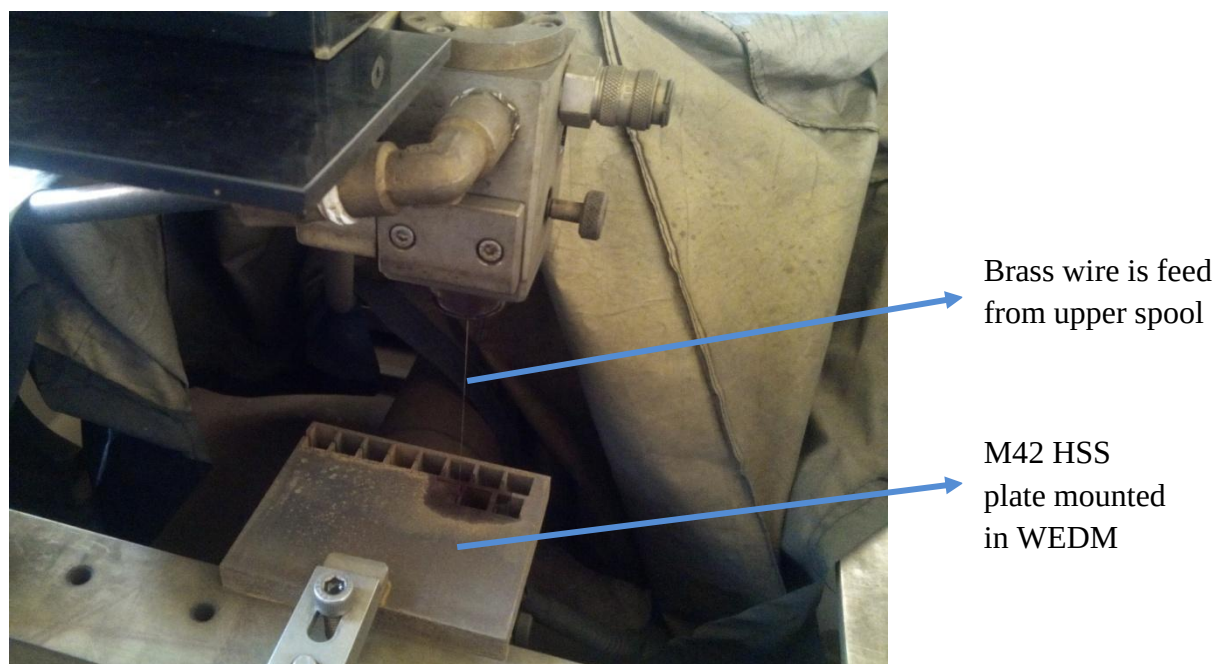


Figure 4.2: Plate Material Blank Mounted on WEDM Machine(Source: MMU, Mullana, Ambala)

4.2.2 Work-Holding Assembly

The work-holding assembly consists of work-table with X-Y coordinate base (Fig. 4.3). The work piece is fitted on the work-holding assembly with the help of vice, bolt or

special work-holding fixture. The lower wire-guide assembly is guarded under the work-holding assembly.



Figure 4.3 Photographic View of Workpiece Holding Assembly

4.2.3 Wire Transport System

The wire transport system holds the wire electrode spool in position to the auxiliary tensioning rollers (Fig. 4.4). The wire electrode from wire spool is moved from rollers in such a manner that it exert minimum tension to the wire. A tensometer is used to check the wire tension during the machining so that it does not rupture.



Figure 4.4 Wire Transport System

4.2.4 The Wire Electrode

The brass wire electrode selected for the experimentation on WEDM was manufactured by VSL Pvt. Ltd. Ludhiana, India. The brass wire comes in the shape of wire spools, which are to be fitted on the machine. The various properties of brass wire(untreated) are shown in table 4.2

Table 4.3: Different properties of brass wire

Material	Chemical composition	Hardness (VH)	Tensile strength	Conductivity (%IACS)
Brass	Cu 63% Zn37%	255	905N/mm ²	21%
Shallow cryogenated brass wire	Cu 63% Zn37%	220	850 N/mm ²	27.9 %



Fig 4.5: View of EDM brass wire spool

4.3 EXPERIMENTAL SETUP FOR CRYOGENIC TREATMENT

The cryogenic treatment of brass wire electrode is done in a cryogenic chamber of cryogenic processor.

4.3.1 Cryogenic Processor

The cryogenic processor consists of cryogenic chamber and a liquid nitrogen cylinder. The dimensions of a cryogenic chamber are 1200x400x400 mm. The photographic view and the specification of the cryogenic processor are given below



Fig 4.6: Cryogenic Processor(source: Insitute of autoparts and handtools(IAHT) Ludhiana).

4.4 CRYOGENIC TREATMENT OF WIRE ELECTRODE

The cryogenic treatments are of two types:

- a) Shallow cryogenic treatment
- b) Deep cryogenic treatment

Here brass wire is given shallow cryogenic treatment for the experimentation purpose.

Comparison of untreated and shallow cryogenated treated brass wire on M42 HSS has to be done in the main experimentation.

a) Shallow cryogenic treatment process

The brass wire electrode was shallow cryogenically treated by the following procedure:

The shallow cryogenic treatment(-110°C) of wire electrode was done using 4- 8-4 cycle (ramp down for four hours-soaking of the wire for eight hours-ramp up for four hours) in a cryogenic processor. In ramp down stage, the temperature is decreased at the rate of 0.56°C per minute from room temperature (~25°C).The temperature is decreased up to -110°C in 4 hours. A typical soak segment will hold the temperature at -110°C for a period of 8 hours. The temperature is increased at the rate of 0.56°C per minute in the ramp up stage and the temperature is brought to room temperature (~25°C).

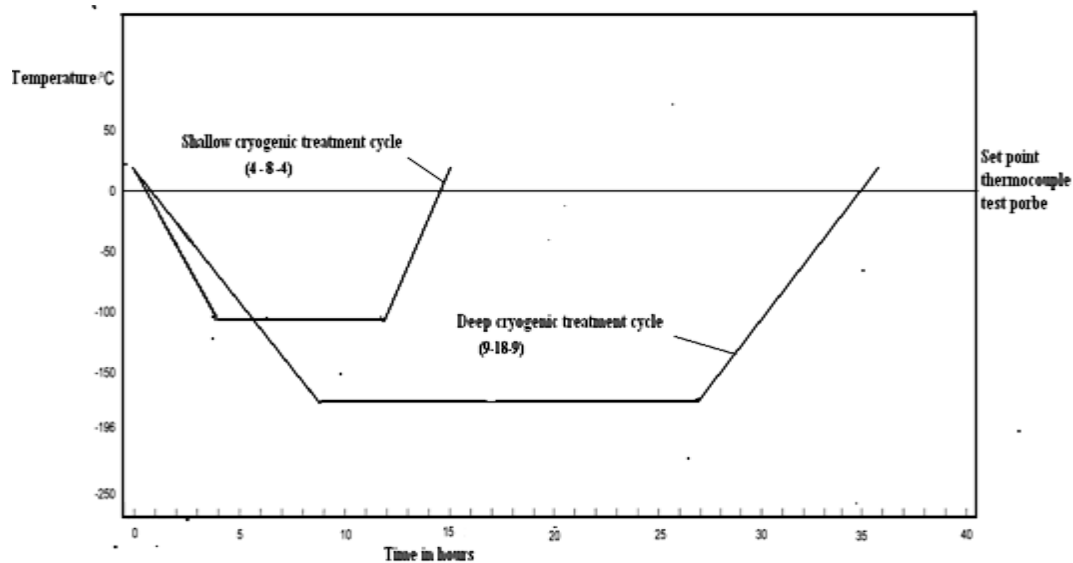


Fig 4.7: Shallow Cryogenic Treatment Cycle for brass wire(source: IAHT, Ludhiana)

b) Deep cryogenic treatment

The deep cryogenic treatment is done at -184°C. The brass wire spool is kept in the cryogenic processor at temperature of -184°C instead of 110°C in case of shallow cryogenic treatment.

4.5 PROCESS PARAMETERS OF WEDM

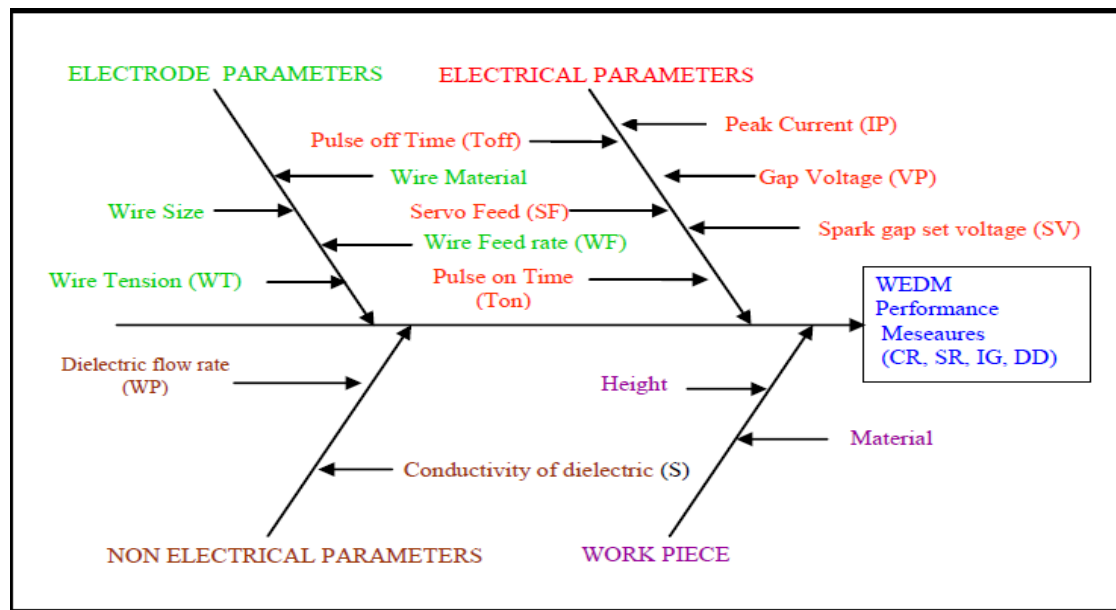


Fig4.8: Ishikawa cause and effect diagram for WEDM processes

4.5.1 Process parameters

A large number of process parameters influence the mechanism of WEDM process, while the machining is in progress. The main effect or even the interaction effects of these parameters influence the machining characteristics in a complex way. As the process of WEDM is controlled by such parameters, a basic outline of these parameters is necessary. The process parameters of the WEDM can be sorted as (i) electrical parameters and (ii) non-electrical parameters.

Table 4.4 shows the primary controllable process parameters available on the selected machine tool.

Table 4.4 Controllable parameters and their ranges

S. No.	Name of Parameter	Symbol	Range	Unit
1	Pulse on time	T_{on}	100-131	machine unit
2	Pulse off time	T_{off}	00-63	machine unit
3	Spark gap voltage	SV	00-99	Volt
4	Wire feed	WF	01-15	m/min

Fundamental electrical parameters comprise of pulse on time(T_{on}), pulse off time (T_{off}), peak current(I_p) and spark gap voltage(SV). The non electrical parameters comprise of wire feed(WF), wire tension(WT) and water pressure(WP).

(i). Pulse on Time (T_{on})

This is commonly referred to as pulse duration, during which period the voltage is applied across the electrodes, i.e. the gap between the work piece and tool (wire electrode). Electric discharge occurs only for the duration of the ON time and all the cutting operation of the work piece material is done during this time. Material removal rate (MRR) increases with increase of T_{on} [Selvakumar et al., 2012]. The single pulse discharge energy increases with increasing T_{on} period, resulting in higher cutting rate (Electronica ecocut technology manual). During each T_{on} , the current increases until it reaches a preset level, which is called the peak current. Spark energy or machining energy = Peak current $\times T_{on}$ [Singh and Bhardwaj, 2011]. With larger T_{on} , more work piece material will melt away producing broader and deeper craters resulting in increased surface roughness (Ra). Also during extended T_{on} , more heat sink into the work piece and spread giving larger recast layer and deeper heat affected zone. To have a long duration of electric discharge, it is possible to select greater value for T_{on} . However, it may cause a short circuit to occur resulting in wire breakage [Godsheya, 2013].

Thus, extreme T_{on} can be counterproductive. When optimum combination of T_{on} for each tool and work piece material is exceeded, cutting speed decreases. To avoid such trouble, pulse off time is inserted. T_{on} range available in the selected machine is 100 to 131(machine unit) in step of 1. The corresponding actual values of T_{on} are from 0.1 to 1.65 μ s in step of 0.05 μ s. The conversion table for T_{on} from machine unit (mu) to actual unit (μ s) is given in Appendix I, Table A [Source: Electronica machine tool manual]

(ii). Pulse off Time (T_{off})

It is commonly referred to as pulse interval. This is the duration of time when no voltage is placed between the work piece and tool (wire electrode).

The pulse off time allows the dielectric fluid to flush out the expelled molten metal and debris (gaseous and solid) and allows the fluid to cool down. Shorter T_{off} time will not allow the expelled work piece material to flush away and the dielectric fluid will not be de ionized. This will cause the next spark to be unstable and slow down cooling. As and

when, the discharge conditions become unstable one can increase the T_{off} period. Higher the T_{off} setting, larger is the pulse off period. With a lower value of T_{off} there are more numbers of discharges in a given time resulting in increase of sparking efficiency. As a result cutting rate also increases [Electronica ecocut, manual]. Pulse interval will affect the speed and stability of the cut [Singh and Bhardwaj, 2011]. The setting range for T_{off} is 00-63 machine unit (mu) in step of 1. The equivalent real values of T_{off} are from 2 to 52 μ s in step of 0.25 to 2 μ s. The translation table for T_{off} from machine unit (mu) to actual unit (μ s) is given in Appendix I, Table B (Source: Electronica machine tool manual)

(iii). Spark Gap Voltage (SV)

SV is a reference voltage for the real gap voltage. The open circuit voltage or supply voltage is the potential between the work piece and wire electrode, when the wire electrode separates from the work piece. Before current flow, the open circuit voltage increase till it establishes an ionization path through the dielectric. Once the current starts to flow, voltage drops and stabilizes at the working gap level. This voltage is known as spark gap voltage (or discharge voltage or cutting voltage). Higher spark gap voltage setting (time taken to achieve this higher voltage setting with the open circuit voltage will be more) means longer discharge waiting time, which improves the flushing condition and hence a stable cut. On the other hand, a machine setting with lower SV value will lessen the discharge waiting time, leading to more number of sparks per unit time. It increases the cutting speed, but compromises surface quality as machining becomes unstable. The spark gap voltage (SV) range for the selected machine tool is 0 to 99 volt in step of 1 volt.

(iv). Wire Feed Rate (WF)

This is a feed rate at which the fresh wire is fed continuously for sparking. Due to spark erosion, the traveling wire electrode becomes thin and brittle. Wire feed is the rate at which the wire electrode actions along the wire guide pathway. It is for all time desirable to set the wire feed to maximum. This will result in less wire rupture, better machining steadiness and a little more cutting speed. Large values of wire feed rate (above 6m/min) are required for working with high pulse power when job cutting rates are higher [Electronica ecocut machine tool manual]. WF setting available in the selected machine tool is 1m/min to 15m/min in step of 1m/min.

(v). Wire Tension (WT)

Wire tension is the factor that can control the tension of wire, in WEDM. If the wire tension is high enough, the wire stays straight, otherwise wire lags behind. This is a gram-equivalent load, with which continuously fed wire is kept under tension, so that it remains straight between the wire guides. While the wire is being fed continuously, appropriate wire tension avoids the unintentional wire deflection from its straight path between the wire guides. Spark induced reaction forces and water pressure cause the thin flexible electrode wire (diameter 0.25 mm) to deflect opposite to the cutting direction.

Minimum tension (for 0 setting) is approximately 200-300 gram which can be set by clutch adjustment provided on the mounting rod. Larger values of wire tension results into regular wire breakage due to larger tensile forces. A small wire tension turns to produce imprecise parts as the wire becomes loose. Higher wire tension is recommended for thick jobs. Wire tension setting available for the given machine tool is 1 to 10 machine unit (mu) in step of 1. Table C in the Appendix I provides nominal values of wire tension in gram aligned with machine unit from 300 to 1380 gram in step of 120 gram. [Source: Electronica ecocut machine tool manual]. For the present study, the wire tension is fixed at setting of 7 indicating tension of 1020 gram.

(vi). Flushing pressure (WP)

The function of dielectric is to obtain stable electric discharge, to flush away debris formed during the machining process and to maintain the wire and work piece cool. Flushing pressure of water dielectric is for selection of flushing input pressure. Higher input pressure is recommended for cutting the high pulse power and jobs of larger thickness. Little pressure is utilized for thin jobs and in machining tidy cuts. The flushing pressure in the selected machine falls under range 0 i.e. low pressure category.

From the above discussion, it is clear that different controllable parameters decide the machining performance such as cutting speed (CS), surface roughness (Ra) and dimensional deviation (DD). In view of the above, four parameters viz. T_{on} , T_{off} , SV and WF are varied during experimentation to study their effect on cutting speed (CS), surface roughness (Ra) and dimensional deviation (DD). Also, there are other parameters which are kept fixed throughout the experimentation.

4.5.2 Selection of control parameters and their ranges

Input process parameters such as T_{on} , T_{off} , SV, WF and their limiting levels were chosen, based on the survey of literature, experience, significance and their relevance.

Table 4.5 Selected control parameters and their ranges for experimentation

S No.	Control Parameters	Symbol	Range(mu)	Range (actual unit)
1	Pulse on time	T_{on}	110-120	0.6-1.1 μ s
2	Pulse off time	T_{off}	45-55	18-36 μ s
3	Spark gap voltage	SV	40-60	40-60V
4	Wire feed	WF	3-7	3-7 m/min

Table 4.6 Fixed parameters

S. No.	Machining Parameters	Fixed operating conditions	Unit
1	Peak current	12	A
2	Dielectric pressure	1	Kg/cm ²
3	Wire tension	1020	gm
4	Work material	M42 HSS	—
5	Work material size	100x80x12	mm
6	Electrode material	(HH) Brass (dia. 0.25mm)	—
7	Electrode polarity	Negative	—
8	Dielectric fluid	De ionized water	—

4.5.3 Fixed process parameters

These are the process parameters which affect the machining performance but are not fully dependent on machine controls, rather are material dependent. They are held constant throughout experimentation. They are shown in Table 4.6.

4.6 SCHEMATIC OF MACHINING

In the present study, experiments are performed on a 4-axis Electronica ecocut wire EDM machine. The electrode material (tool) used is 0.25 mm diameter half hard brass wire. The work material used is M42 HSS of dimension 100 mm x 80 mm x 12 mm. A small gap of 0.025 to 0.05 mm is maintained between the work piece and wire electrode. Spark is initiated when high voltage is applied between electrode and work piece at smallest point distance. The high energy density erodes material from both the work piece and wire by local melting and vaporizing. While the machining is continued, the machining zone is continuously flushed with dielectric fluid passing through the nozzles, on both sides of the work piece, which removes the eroded particles, produced during spark erosion. The schematic diagram while the machining process is in progress is shown in Fig 4.1. A waste wire box located at the bottom of the machine collects the used electrode wire. The wires once used cannot be reused and discarded.

4.7 EXPERIMENTAL SET-UP

The work material in the form of rectangular plate having dimensions 100 mm x 80 mm x 12 mm is installed in the work table for experimentation work. Fig 4.1 shows the machine tool above, Fig 4.2 shows the work piece material mounted on the work table and Fig 4.9 show the job profile during machining.

Table 4.7 Control factors, Codes, values and their levels

Parameters	Codes	Values (levels)		
		Low	Medium	High
T_{on} (μs)	A	110 (-1)	115 (0)	120 (+1)
T_{off} (μs)	B	45 (-1)	50 (0)	55 (+1)
SV (V)	C	40 (-1)	50 (0)	60 (+1)
WF (m/min)	D	3 (-1)	5 (0)	7 (+1)

The experiments (total 58 no_s) are performed separately, firstly 29 experiments by using untreated brass wire and then 29 experiments by using cryogenated brass wire according to Box-Behenken Design as illustrated in Table .

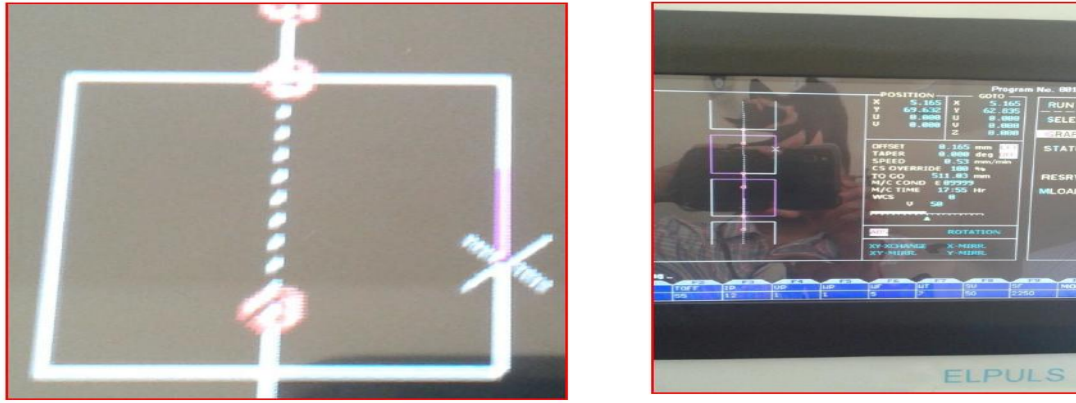


Figure 4.9: Job profile during machining

4.8 PROCEDURE FOR EXPERIMENTATION

Experiments are performed on a 4-axes Electronica ecocut CNC wire EDM machine according to Box-Behenken design (BBD) approach using design expert 6.0.8 software. In the present study there are four control factors and their values and levels are shown in Table 4.7. Table 4.6 gives information about the parameters and their values which are kept fixed during the experiment. A rectangular plate of super HSS M42(100mm× 80mm × 12mm) is taken as work piece.

Prior to the commencement of the experimental work, the machine tool and its surroundings are inspected for their fitness to conduct the machining experiments. Following steps are followed to perform the machining (cutting) operation.

- (i) The work piece is mounted and clamped on the main work table (called x-y table) of the machine (Fig 4.2) and is checked for any perpendicularity error using a dial indicator.
- (ii) The cutting tool (0.25mm dia. Brass wire) is installed in the machine by using the spool pin and mounted pulleys, of the wire drive mechanism (Fig 4.10) and made vertical, using a verticality block between the upper and lower wire guides (Fig 4.12). Fig 4.11 demonstrates its schematic and Fig 4.13 denotes the wire path.
- (iii) A reference point on the ground edge of the work piece is selected to set the working co-ordinate system.
- (iv) Tool path for movement of wire is designated by developing a computer program using ELCAM software supplied by Electronica machine tool manufacturer.

- (v) The Machine is manually moved to the starting point, where cutting is to begin. A zero is set at the point where initial sparking starts.
- (vi) Process parameters are set at the specified levels and the machine is run according to the suitable program A 10mm x 10mm square punch (sample) is machined (cut) out from the work piece. Likewise 58 samples are obtained according to BBD, firstly 29 by using untreated brass wire and then 29 by using the shallow cryogented treated brass wire. Fig 4.14 shows job during machining process and fig 4.15 depicts the complete job profile after WEDM experiments. Table 4.8 shows design matrix for main experimentation.

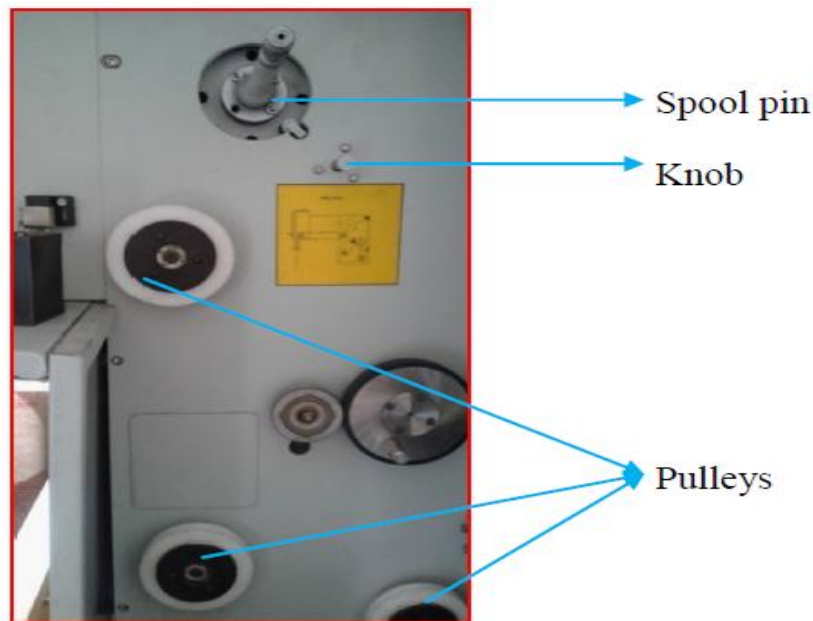


Fig 4.10 Wire drive mechanism

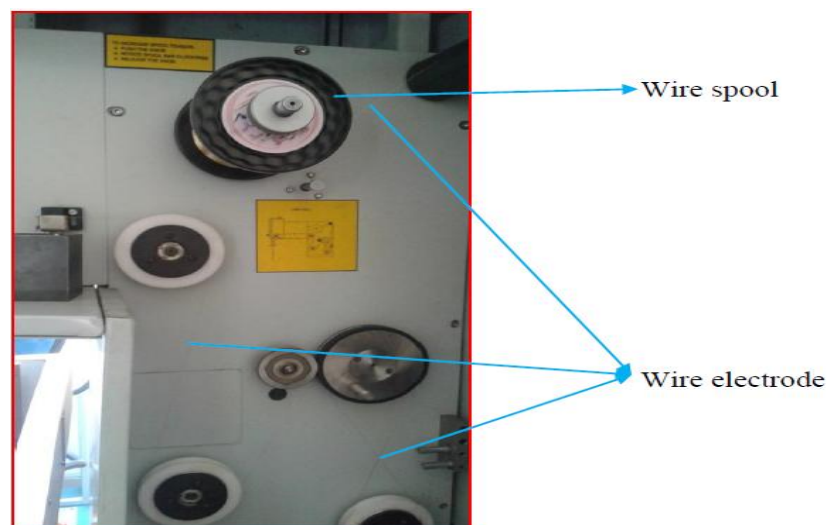


Fig 4.11 Wire installation

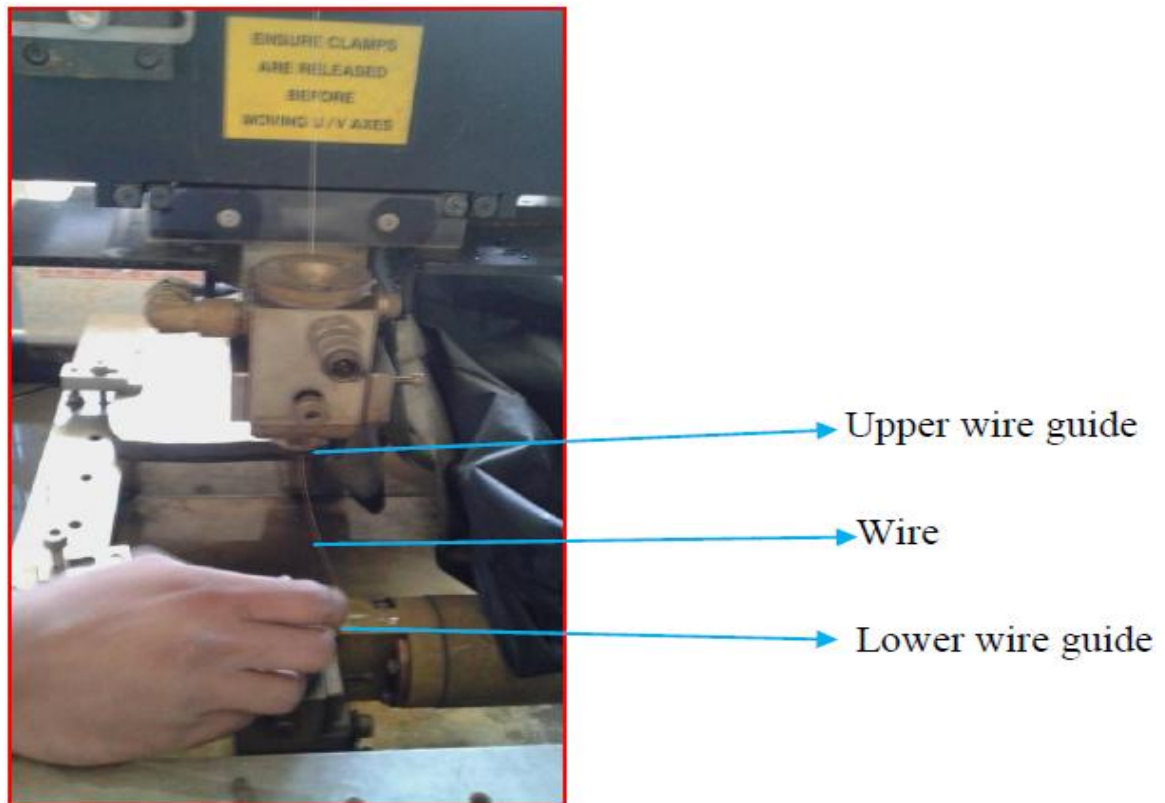


Fig 4.12 Wire guides

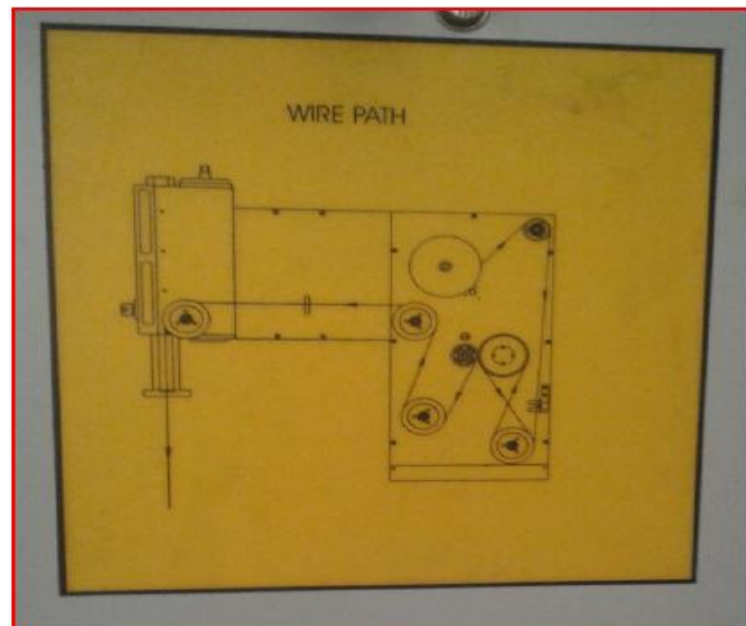


Fig 4.13 Wire path



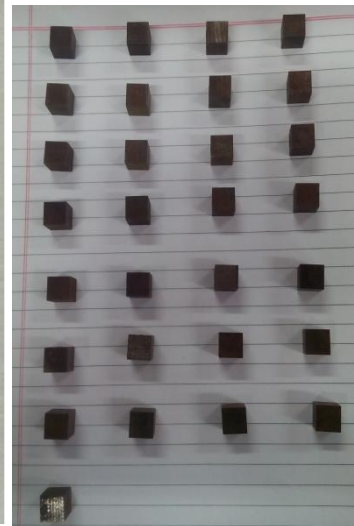
Fig 4.14 Job view during machining



(a)



(b)



(c)

Fig 4.15 (a) Complete job profile after WEDM (b) Specimens cut with non-cryogenated wire (c) Specimens cut with cryogenated wire

Table 4.8 Design matrix for main experimentation

			Factor 1	Factor 2	Factor 3	Factor 4
Std	Run	Block	A:Pulse on time(mu)	B:Pulse off time(mu)	C:Spark gap voltage(V)	D:Wire Feed(m/min)
2	1	Block 1	120	45	50	5
15	2	Block 1	115	45	60	5
24	3	Block 1	115	55	50	7
7	4	Block 1	115	50	40	7
27	5	Block 1	115	50	50	5
6	6	Block 1	115	50	60	3
25	7	Block 1	115	50	50	5
20	8	Block 1	120	50	60	5
10	9	Block 1	120	50	50	3
16	10	Block 1	115	55	60	5
18	11	Block 1	120	50	40	5
11	12	Block 1	110	50	50	7
12	13	Block 1	120	50	50	7
4	14	Block 1	120	55	50	5
9	15	Block 1	110	50	50	3
28	16	Block 1	115	50	50	5
19	17	Block 1	110	50	60	5
5	18	Block 1	115	50	40	3
3	19	Block 1	110	55	50	5
22	20	Block 1	115	55	50	3
29	21	Block 1	115	50	50	5
21	22	Block 1	115	45	50	3
8	23	Block 1	115	50	60	7
13	24	Block 1	115	45	40	5
1	25	Block 1	110	45	50	5
17	26	Block 1	110	50	40	5
26	27	Block 1	115	50	50	5
14	28	Block 1	115	55	40	5
23	29	Block 1	115	45	50	7

Legend: T_{on} - Pulse on time, T_{off} - Pulse off time, SV- Spark gap voltage, WF- wire feed rate

4.9 MEASUREMENT OF PERFORMANCE PARAMETERS

In this study most important output performances in WEDM such as cutting speed, surface roughness and dimensional deviation were considered for optimizing the machining parameters.

4.9.1 Measurement of cutting speed (CS)

Cutting speed is a measure of the rate of cutting operation and is expressed quantitatively in mm/min. As the machining process is in progress, the instantaneous cutting speed is displayed on the monitor of the machine tool (Fig 4.16). This instantaneous cutting speed is noted at distances of 2.5 mm, 5mm and 7 mm from the initiation of the cut along a particular axis. The same procedure is adopted for all four sides of the cutting surfaces of the unit. This is done to ensure that readings are noted, only when the cutting is stabilized properly. The average of the twelve (8) readings obtained so, provides the performance measure cutting speed. In WEDM, cutting speed (CS) is a desirable characteristic and should be as high as possible for increased productivity.



Fig 4.16 Measurement of cutting speed

4.9.2 Measurement of surface roughness (Ra)

Surface roughness is a measure of the texture of a surface. It is quantified by the vertical deviations of a real surface from its ideal form. Generally, average roughness (Ra) is used to indicate the profile of a surface. Surface finish is an important performance measure which decides the manufacturing quality of WEDMed components. Surface roughness (Ra) refers to the short wavelength and high frequency closely spaced irregularities on the machined surface, caused by the nature and the actions of the manufacturing processes.

Average surface roughness (R_a) is easy to define, as it measures and gives a general description of surface amplitude.

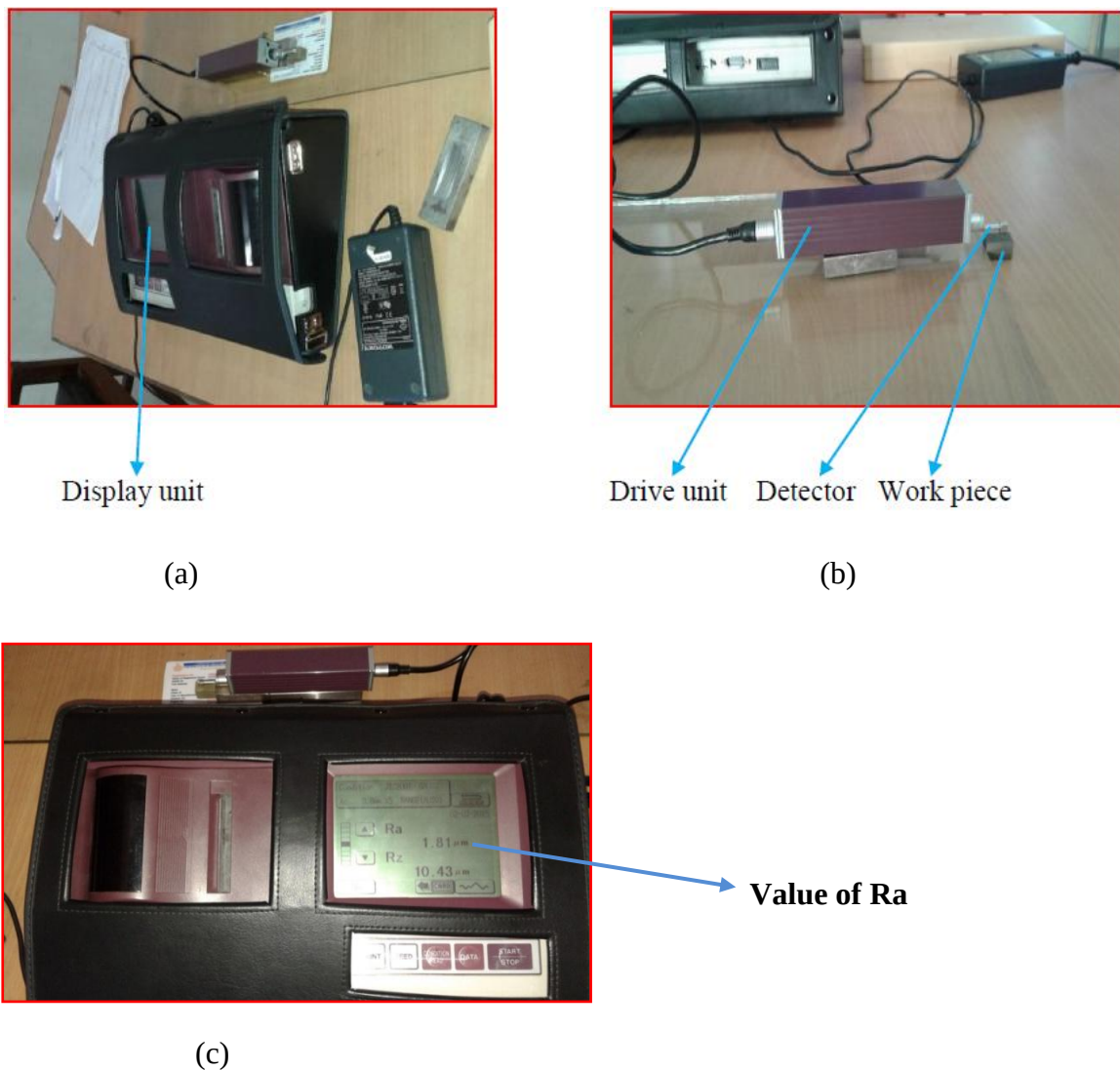


Fig 4.17 (a),(b) of surface roughness (R_a) tester SurftestSJ-301 (c) Measurement of R_a (Source: Meterology Lab, Thapar University, Patiala)

The surface roughness (R_a) of the machined surface is measured, after all the experimental runs are performed, by using a contact type stylus based surface roughness tester Mitutoyo surftestSJ-301 (series no.178), having a display range of 0.01 to 100 μm as shown in Fig. 4.17(a),(b). The cut off length is 0.8 mm and evaluation length is 4.0 mm. R_a is measured at 3 places perpendicular to the direction of cut of the machined surface and mean of the three readings denoted average surface roughness. Fig 4.17 (c) illustrates the measurement of R_a values.

Every time, an experimental run is implemented, a particular set of parameter combination is selected and the work piece is engrave as per the explained procedure (4.8) and the performance measures are noted down. Table 4.9 and table 4.10 summarizes the results obtained from 29 experimental runs individually by using untreated and cryogenated brass wire.

4.9.3 Measurement of dimensional deviation(DD)

The cross-section of the sample workpieces is measured with the assistance of a Mitutoyo's digital micrometer having the least count of 0.001 mm and the dimensional deviation of the calculated dimension is measured in percentage using the following expression:

$$\text{Dimensional deviation} = \frac{\text{Observed value} - \text{Actual value}}{\text{Actual value}} \times 100$$

The instrument set up for the measurement of dimensional deviation is shown in fig 4.18



Fig: 4.18 Profile projector for dimensional deviation measurement

Table 4.9 Design matrix and output responses-I for untreated brass wire

			Factor 1	Factor 2	Factor 3	Factor 4	Response 1	Response 2	Response 3
Std	Run	Block	A:Pulse on time(mu)	B:Pulse off time(mu)	C:Spark gap voltage(V)	D:Wire Feed(mm/min)	Cutting Speed(mm/min)	Surface Roughness (μs)	Dimensional Deviation (mm)
2	1	Block 1	120	45	50	5	1.04	2.36	0.12
15	2	Block 1	115	45	60	5	0.48	1.46	0.02
24	3	Block 1	115	55	50	7	0.4	1.27	0.06
7	4	Block 1	115	50	40	7	0.68	1.55	0.07
27	5	Block 1	115	50	50	5	0.53	1.23	0.01
6	6	Block 1	115	50	60	3	0.36	1.45	0.02
25	7	Block 1	115	50	50	5	0.53	1.24	0.05
20	8	Block 1	120	50	60	5	0.55	1.47	0.04
10	9	Block 1	120	50	50	3	0.78	1.68	0.02
16	10	Block 1	115	55	60	5	0.29	1.37	0.02
18	11	Block 1	120	50	40	5	1.02	2.97	0.1
11	12	Block 1	110	50	50	7	0.36	1.45	0.01
12	13	Block 1	120	50	50	7	0.71	1.47	0.12
4	14	Block 1	120	55	50	5	0.6	1.62	0.07
9	15	Block 1	110	50	50	3	0.34	1.28	0.09
28	16	Block 1	115	50	50	5	0.49	1.45	0.03
19	17	Block 1	110	50	60	5	0.24	1.75	0
5	18	Block 1	115	50	40	3	0.67	1.32	0.01
3	19	Block 1	110	55	50	5	0.27	1.49	0.08
22	20	Block 1	115	55	50	3	0.39	1.15	0.04
29	21	Block 1	115	50	50	5	0.49	1.46	0.02
21	22	Block 1	115	45	50	3	0.7	1.31	0.06
8	23	Block 1	115	50	60	7	0.34	1.53	0.01
13	24	Block 1	115	45	40	5	0.94	1.85	0.06
1	25	Block 1	110	45	50	5	0.49	1.26	0.05
17	26	Block 1	110	50	40	5	0.49	1.39	0.03
26	27	Block 1	115	50	50	5	0.5	1.43	0.04
14	28	Block 1	115	55	40	5	0.51	1.23	0.05
23	29	Block 1	115	45	50	7	0.67	1.19	0.07

Table 4.10 Design matrix and output responses for cryogenated treated brass wire

			Factor 1	Factor 2	Factor 3	Factor 4	Response 1	Response 2	Response 3
Std	Run	Block	A:Pulse on time(mu)	B:Pulse off time(mu)	C:Spark gap voltage(V)	D:Wire Feed(m/min)	Cutting Speed(mm/min)	Surface Roughness(μs)	Dimensional Deviation(mm)
2	1	Block 1	120	45	50	5	1.14	1.75	0.12
15	2	Block 1	115	45	60	5	0.54	1.32	0.02
24	3	Block 1	115	55	50	7	0.51	1.1	0.06
7	4	Block 1	115	50	40	7	0.74	1.35	0.07
27	5	Block 1	115	50	50	5	0.63	1.22	0.01
6	6	Block 1	115	50	60	3	0.46	1.22	0.02
25	7	Block 1	115	50	50	5	0.63	1.23	0.05
20	8	Block 1	120	50	60	5	0.55	1.48	0.04
10	9	Block 1	120	50	50	3	0.85	1.6	0.02
16	10	Block 1	115	55	60	5	0.39	1.26	0.02
18	11	Block 1	120	50	40	5	1.08	2.18	0.1
11	12	Block 1	110	50	50	7	0.47	1.18	0.01
12	13	Block 1	120	50	50	7	0.81	1.45	0.12
4	14	Block 1	120	55	50	5	0.63	1.34	0.07
9	15	Block 1	110	50	50	3	0.46	1.19	0.09
28	16	Block 1	115	50	50	5	0.59	1.36	0.03
19	17	Block 1	110	50	60	5	0.27	1.76	0
5	18	Block 1	115	50	40	3	0.75	1.31	0.01
3	19	Block 1	110	55	50	5	0.37	1.29	0.08
22	20	Block 1	115	55	50	3	0.49	1.12	0.04
29	21	Block 1	115	50	50	5	0.59	1.45	0.02
21	22	Block 1	115	45	50	3	0.78	1.31	0.06
8	23	Block 1	115	50	60	7	0.44	1.24	0.01
13	24	Block 1	115	45	40	5	1.04	1.5	0.06
1	25	Block 1	110	45	50	5	0.56	1.13	0.05
17	26	Block 1	110	50	40	5	0.59	1.29	0.03
26	27	Block 1	115	50	50	5	0.58	1.34	0.04
14	28	Block 1	115	55	40	5	0.62	1.24	0.05
23	29	Block 1	115	45	50	7	0.77	1.26	0.07

CHAPTER 5

RESULTS AND DISCUSSION

This chapter presents the relevance of Response Surface Methodology (RSM). The selected process variables such as pulse on time (T_{on}), pulse off time (T_{off}), Spark gap voltage (SV) and wire feed (WF) were varied up to 3 levels and Box-Behnken Design (BBD) was adopted to design the experiments.

In the present study, all the design plots and analysis are carried out using “Design Expert DX.6” statistical software. Fig 5.1 demonstrates the flow chart of the different steps implicated in the investigation of results and optimization. These strides are examined in the accompanying areas and subsections.

5.1 ASSESSMENT OF THE ADEQUACY OF MODEL FITTING

In this section, appropriateness of the model is investigated and the quality of the fit is ascertained. To check the adequacy of the model, three different tests are performed such as sequential model sum of squares, lack of fit (LOF) tests and model summary statistics for cutting speed (CS), gap current (I_g) and surface roughness (R_a). Normally, a model with highest F-value and lower p-value is selected [Montgomery, 2002].

The LOF test is a measure of the failure of the model to represent data in the experimental domain at which, points are not included in the regression and variations are observed in the model that cannot be accounted by random error [Montgomery, 2002]. For the model to be fit, this test should indicate insignificant lack of fit.

A p-value, greater than 0.05 nullifies the LOF model to the response data and the model can be utilized for prediction of response parameter for 95% of confidence interval.

Model summary statistics gives insights about standard deviation, R^2 , Predicted R^2 and Prediction error sum of squares (PRESS) of the model. For the most part, a model with lesser standard deviation, R^2 more like 1 and littler estimation of PRESS is chosen [Montgomery, 2002].

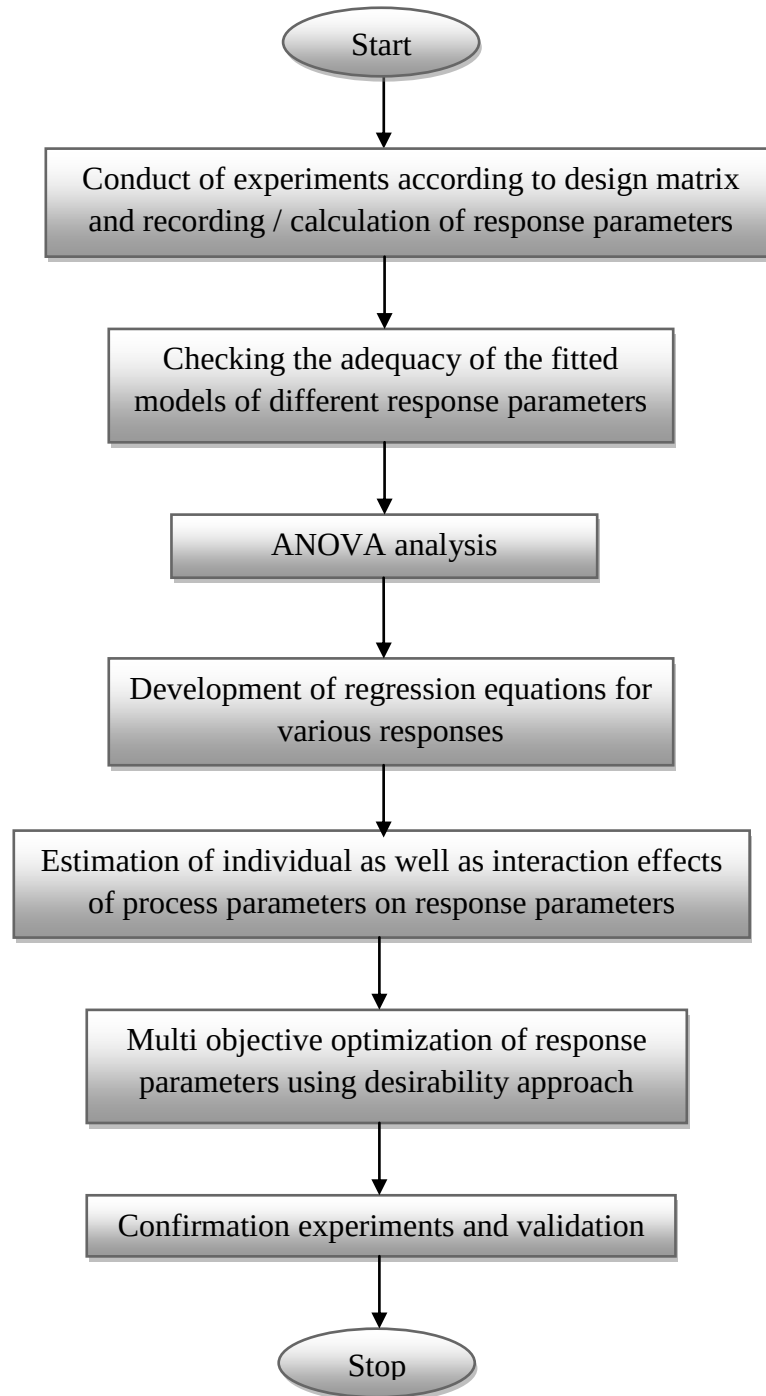


Figure 5.1 Methodology of the experimentation and analysis of results

Tables 5.1-5.18 show the data related to above three tests for cutting speed, surface roughness and dimensional deviation for non cryogenic and cryogenated treatment respectively. Quadratic models are recommended for the cutting speed, surface roughness and dimensional deviation, by means of the Design Expert[®] software subsequent to performing above mentioned three tests.

5.2 ANALYSIS OF VARIANCE AND MATHEMATICAL MODELS OF RESPONSE CHARACTERISTICS

Analysis of variance (ANOVA) is performed to statistically analyze the results. ANOVA checks the value of R^2 as it explains the ratio of variability explained by the model to the total variability inherent in the observed data of experiments. It also shows adequate precision which measures signal to noise ratios. A ratio greater than 4 indicates the model to be fit. Process variables having p-value less than 0.05 are considered significant terms for the given response parameters. The backward elimination method eliminates the insignificant terms to adjust the fitted quadratic models and in the present work backward elimination process with α to exit = 0.05 is used to eliminate the insignificant terms.

The results and analysis for different responses from the application of ANOVA test for untreated and cryogenated treated samples are discussed in following sections.

5.2.1 For untreated/non cryogenated samples

Table 5.1 Adequacy checking of model of cutting speed

Sequential Model Sum of Squares						
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Prob.> F (p-value)	Remarks
Mean	8.67	1	8.67			
Linear	1.16	4	0.2995	0.98	< 0.0001	
2FI	0.041	6	0.006875	3.93	0.0110	
Quadratic	0.027	4	0.006754	20.99	< 0.0001	Suggested
Cubic	0.002650	8	0.000331	1.07	0.4801	Aliased
Residual	0.001855	6	0.000309			
Total	9.9129	29	0.34			
Lack of Fit Tests						
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Prob.> F (p-value)	Remarks
Linear	0.071091	20	0.003555	8.463177	0.0255	
2FI	0.029841	14	0.002131	5.074947	0.0642	
Quadratic	0.002825	10	0.000283	0.672619	0.7222	Suggested
Cubic	0.000175	2	0.0000875	0.208333	0.8202	Aliased
Pure Error	0.00168	4	0.00042			
Model Summary Statistics						
Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	Remarks
Linear	0.055	0.9412	0.9314	0.9115	0.11	
2FI	0.042	0.9745	0.9604	0.9322	0.084	
Quadratic	0.018	0.9964	0.9927	0.9847	0.019	Suggested
Cubic	0.018	0.9985	0.9930	0.9775	0.028	Aliased

Table 5.2 Adequacy checking of model of surface roughness

Sequential Model Sum of Squares						
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Prob.> F (p-value)	Remarks
Mean	65.79	1	65.79			
Linear	1.01	4	0.25	2.14	0.1073	
2FI	1.23	6	0.20	2.29	0.0807	
Quadratic	1.11	4	0.28	7.77	< 0.0016	Suggested
Cubic	0.40	8	0.050	2.93	0.1036	Aliased
Residual	0.10	6	0.017			
Total	69.63	29	2.40			
Lack of Fit Tests						
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Prob.> F (p-value)	Remarks
Linear	2.78	20	0.14	10.23	0.0180	
2FI	1.55	14	0.11	8.16	0.0279	
Quadratic	0.44	10	0.044	3.27	0.1322	Suggested
Cubic	0.047	2	0.024	1.74	0.2857	
Pure Error	0.054	4	0.014			
Model Summary Statistics						
Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	Remarks
Linear	0.34	0.2626	0.1397	-0.1351	4.36	
2FI	0.30	0.5820	0.3498	-0.2951	4.97	
Quadratic	0.19	0.8702	0.7405	0.3119	2.64	Suggested
Cubic	0.13	0.9736	0.8766	-0.7947	6.89	

Table 5.3 Adequacy checking of model of dimensional deviation

Sequential Model Sum of Squares						
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Prob.> F (p-value)	Remarks
Mean	0.065	1	0.065			
Linear	0.008483	4	0.002121	2.30	0.0877	
2FI	0.011	6	0.001867	3.08	0.0295	
Quadratic	0.008771	4	0.002193	14.45	< 0.0001	Suggested
Cubic	0.001017	8	0.0001271	0.69	0.6958	
Residual	0.001108	6	0.0001847			
Total	0.095	29	0.003286			
Lack of Fit Tests						
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Prob.> F (p-value)	Remarks
Linear	0.021	20	0.001055	4.22	0.0859	
2FI	0.009896	14	0.0007069	2.83	0.1628	
Quadratic	0.001125	10	0.0001125	0.45	0.8606	Suggested
Cubic	0.0001083	2	0.00005417	0.22	0.8141	
Pure Error	0.001000	4	0.0002500			
Model Summary Statistics						
Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	Remarks
Linear	0.030	0.2774	0.1570	-0.0921	0.033	
2FI	0.025	0.6437	0.4457	-0.002	0.031	
Quadratic	0.012	0.9305	0.8610	0.7370	0.008043	Suggested
Cubic	0.014	0.9638	0.8309	0.4388	0.017	

5.2.2 For cryogenated wire

Table 5.4 Adequacy checking of model of cutting speed

Sequential Model Sum of Squares						
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Prob.> F (p-value)	Remarks
Mean	11.59	1	11.59			
Linear	1.12	4	0.28	74.89	< 0.0001	
2FI	0.056	6	0.009287	4.86	0.0041	
Quadratic	0.017	4	0.004306	3.51	0.0349	Suggested
Cubic	0.014	8	0.001700	2.85	0.1093	
Residual	0.003578	6	0.0005964			
Total	12.80	29	0.44			
Lack of Fit Tests						
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Prob.> F (p-value)	Remarks
Linear	0.088	20	0.004390	7.57	0.0312	
2FI	0.032	14	0.002291	3.95	0.0970	
Quadratic	0.015	10	0.001486	2.56	0.1890	Suggested
Cubic	0.001258E-003	2	0.0006292	1.08	0.4204	
Pure Error	0.002320	4	0.0005800			
Model Summary Statistics						
Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	Remarks
Linear	0.061	0.9258	0.9135	0.8863	0.14	
2FI	0.044	0.9717	0.9560	0.9176	0.10	
Quadratic	0.035	0.9859	0.9717	0.9266	0.089	Suggested
Cubic	0.024	0.9971	0.9863	0.8479	0.18	

Table 5.5 Adequacy checking of surface roughness

Sequential Model Sum of Squares						
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Prob.> F (p-value)	Remarks
Mean	53.72	1	53.72			
Linear	0.42	4	0.11	2.45	0.0732	
2FI	0.44	6	0.073	2.22	0.0888	
Quadratic	0.49	4	0.12	16.88	<0.0001	Suggested
Cubic	0.008767	8	0.001096	0.071	0.9993	
Residual	0.093	6	0.016			
Total	55.17	29	1.90			
Lack of Fit Tests						
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Prob.> F (p-value)	Remarks
Linear	0.99	20	0.050	5.38	0.0570	
2FI	0.56	14	0.040	4.29	0.0848	
Quadratic	0.065	10	0.006488	0.70	0.7051	Suggested
Cubic	0.056	2	0.028	3.03	0.1579	
Pure Error	0.037	4	0.009250			
Model Summary Statistics						
Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	Remarks
Linear	0.21	0.2903	0.1720	-0.0966	1.59	
2FI	0.18	0.5920	0.3654	-0.2841	1.87	
Quadratic	0.085	0.9299	0.8599	0.7032	0.43	Suggested
Cubic	0.12	0.9360	0.7011	-4.5971	8.14	

Table 5.6 Adequacy checking of model of dimensional deviation

Sequential Model Sum of Squares						
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Prob.> F (p-value)	Remarks
Mean	0.065	1	0.065			
Linear	0.008483	4	0.002121	2.30	0.0877	
2FI	0.011	6	0.001867	3.08	0.0295	
Quadratic	0.008771	4	0.002193	14.45	<0.0001	Suggested
Cubic	0.001017	8	0.0001271	0.69	0.6958	
Residual	0.001108	6	0.0001847			
Total	0.095	29	0.003286			
Lack of Fit Tests						
Source	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	Prob.> F (p-value)	Remarks
Linear	0.021	20	0.001055	4.22	0.0859	
2FI	0.009896	14	0.0007069	2.83	0.1628	
Quadratic	0.001125	10	0.0001125	0.45	0.8606	Suggested
Cubic	0.0001083	2	0.00005417	0.22	0.8141	
Pure Error	0.001000	4	0.0002500			
Model Summary Statistics						
Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	Remarks
Linear	0.030	0.2774	0.1570	-0.0921	0.033	
2FI	0.025	0.6437	0.4457	-0.0002	0.031	
Quadratic	0.012	0.9305	0.8610	0.7370	0.008043	Suggested
Cubic	0.014	0.9638	0.8309	0.4388	0.017	

5.2.3 For non-cryogenated experiments

5.2.3.1 Analysis of variance and mathematical model for cutting speed

As talked about in segment 5.1, quadratic model for machining rate is suggested by Design Expert6.0.7® programming. Table 5.7 shows ANOVA for the quadratic model at 95% confidence level. It demonstrates that F-estimation of model is 317.84 and comparing p-worth is under 0.001. It suggests that there is just a 0.01% chance that such extensive F-estimation of model can happen because of noise. Additionally, lack of fit of 0.6106 infers that it is not huge in respect to pure error. Subsequently, quadratic model get significant at 95% confidence level. The other imperative coefficient R^2 , which is called determination coefficient, is characterize as the proportion of the disclosed variety to the aggregate variety and is a measure of the level of fit. At the point when R^2 ways to deal with solidarity or 1, the response model fits better to the genuine information and shows less distinction between the anticipated qualities and real values. The acquired qualities are predicted R^2 of 0.9827 is in sensible concurrence with the balanced R^2 of 0.9912. Figure 5.2 shows normal probability plot of residuals for cutting speed. It plainly demonstrates that errors are ordinarily appropriated as the greater part of the residuals are grouped around straight line. It is watched that, regression model is actually all around fitted with actual values. As adequate precision is 64.56 as appeared in Table 5.9, in this way the quadratic model can be utilized to explore in the design space.

The mathematical relationship for correlating the cutting speed and the considered process variables is obtained as follows:

$$\begin{aligned} \text{Cutting speed} = & +12.01605 - 0.25786 * \text{Pulse on time} + 0.010068 * \text{Pulse off time} + \\ & 0.049417 * \text{Spark gap voltage} + 0.25542 * \text{Wire Feed} + 0.002069 * \text{Pulse on time}^2 + \\ & 0.0015193 * \text{Pulse off time}^2 - 0.0022 * \text{Pulse on time} * \text{Pulse off time} - 0.0011 * \text{Pulse} \\ & \text{on time} * \text{Spark gap voltage} - 0.00225 * \text{Pulse on time} * \text{Wire Feed} + 0.0012 * \text{Pulse off} \\ & \text{time} * \text{Spark gap voltage} \end{aligned}$$

(5.1)

Figure 5.3 shows plot of experimental and predicted data for machining rate. It depicts that Equation 5.1 is adequate to represent the actual relationship between process parameters and responses [Taweel, 2009].

Table 5.7 ANOVA for response surface of reduced quadratic model of cutting speed

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	Remarks	% Contribution
Model	1.22986	10	0.12299	317.835	< 0.0001	Significant	
A	0.52501	1	0.52501	1356.79	< 0.0001	Significant	42.74
B	0.2883	1	0.2883	745.062	< 0.0001	Significant	23.38
C	0.35021	1	0.35021	905.054	< 0.0001	Significant	28.22
D	0.00053	1	0.00053	1.37831	0.2557	Not significant	0.042
A ²	0.01847	1	0.01847	47.737	< 0.0001	Significant	1.45
B ²	0.00996	1	0.00996	25.7334	< 0.0001	Significant	0.77
AB	0.0121	1	0.0121	31.2704	< 0.0001	Significant	0.96
AC	0.0121	1	0.0121	31.2704	< 0.0001	Significant	0.96
AD	0.00203	1	0.00203	5.23327	0.0345	Significant	0.16
BC	0.0144	1	0.0144	37.2143	< 0.0001	Significant	1.12
Residual	0.00697	18	0.00039				
Lack of Fit	0.00529	14	0.00038	0.89882	0.6106	Not significant	
Pure Error	0.00168	4	0.00042				
Cor Total	1.23682	28					
Std. Dev0.020R-Squared0.9944 Mean0.55Adj R-Squared0.9912 C.V.3.60Pred R-Squared0.9827 PRESS0.021Adeq Precision64.560							
Legend: A- Pulse on time, B- Pulse off time, C- Spark gap set voltage, D- Wire Feed Rate							

DESIGN-EXPERT Plot
Cutting Speed

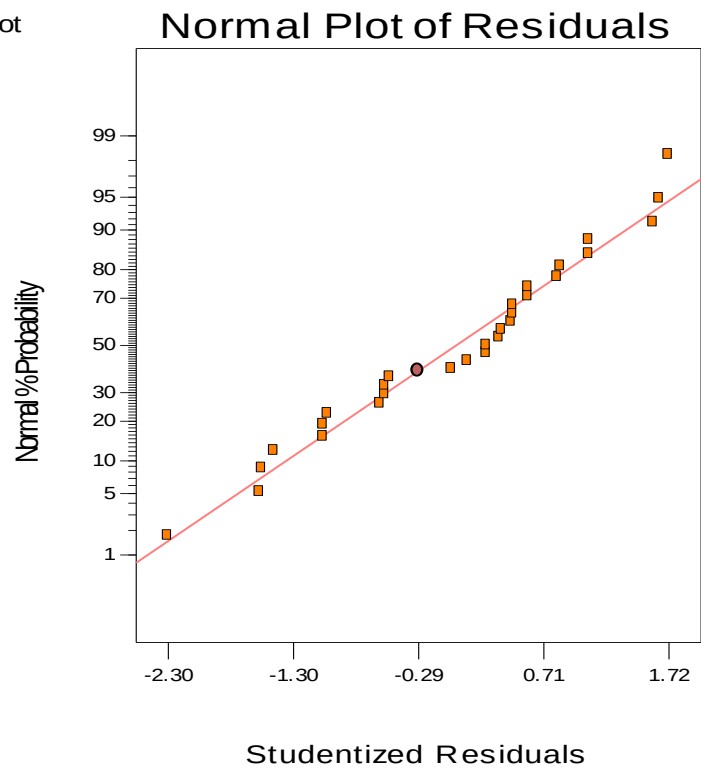


Figure 5.2 Normal probability plots of residuals for cutting speed

DESIGN-EXPERT Plot
Cutting Speed

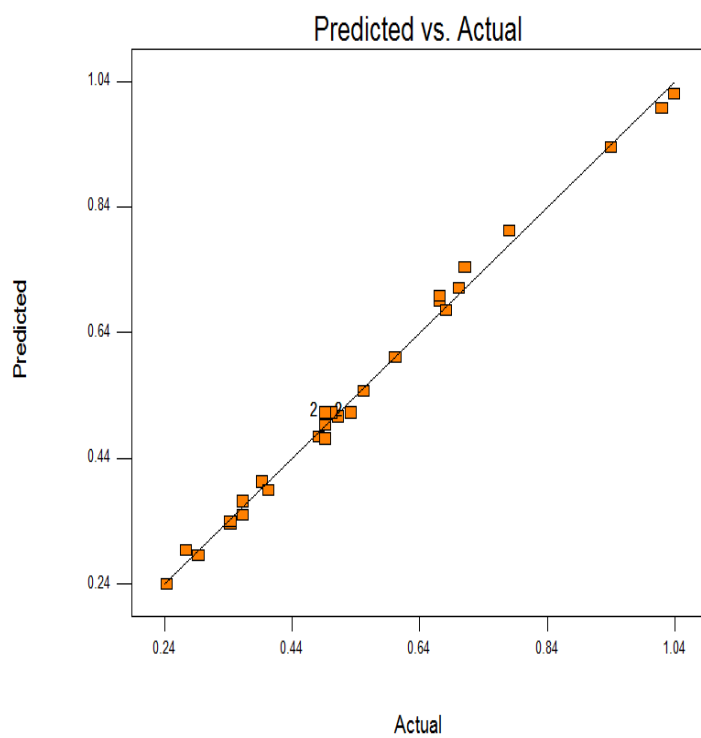


Figure 5.3 Plot of actual versus predicted of cutting speed data

5.2.3.2 Analysis of variance and mathematical model for surface roughness

Quadratic model for surface roughness is proposed by the Design expert 6.0[®] software. Adequacy of the model is checked using ANOVA as discussed in section 5.1 at 95 % confidence level and presented in Table 5.8. It indicates that F-value of the model is 12.34 and corresponding p-value is less than 0.0001. Thus, quadratic model is significant at 95% confidence level. The p-value of lack of fit is greater than 0.05. Thus, lack of fit is insignificant. Further, lack of fit value of 0.1468 implies that it is not significant relative to pure error. Moreover, R² value is 0.8045. This confirms that accuracy and general ability of polynomial model is good. Further, predicted R² of 0.5121 is in reasonable agreement with adjusted R² of 0.7393 and it indicates a high correlation between observed values and predicted values. Figure 5.4 shows normal probability plot of residuals for surface roughness. It clearly shows that errors are normally distributed as most of the residuals are clustered around the straight line. The plot of observed versus predicted values as presented in Figure 5.5 indicate that observed response are closer to the predicted values and model can define actual relationship between process parameters and output. Adequate precision value is 14.932 and it suggests that quadratic model can be used to navigate in the design space.

$$\begin{aligned} \text{Surface Roughness} = & +69.08051 - 2.05225 * \text{Pulse on time} + 1.09383 * \text{Pulse off time} + \\ & 0.83341 * \text{Spark gap voltage} + 0.013267 * \text{Pulse on time}^2 + 0.00225 * \text{Spark gap} \\ & \text{voltage}^2 - 0.0097 * \text{Pulse on time} * \text{Pulse off time} - 0.0093 * \text{Pulse on time} * \text{Spark gap} \\ & \text{voltage} \end{aligned}$$

(5.2)

Table 5.8 ANOVA for response surface of reduced quadratic model of surface roughness

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	Remarks	% Contribution
Model	3.09	7	0.44	12.34	< 0.0001	Significant	
A	0.73	1	0.73	20.28	0.0002	Significant	19.01
B	0.14	1	0.14	3.94	0.0604	Significant	3.64
C	0.14	1	0.14	3.82	0.0641	Significant	3.64
A ²	0.76	1	0.76	21.24	0.0002	Significant	19.79
C ²	0.35	1	0.35	9.81	0.005	Significant	9.11
AB	0.24	1	0.24	6.58	0.018	Significant	6.25
AC	0.86	1	0.86	24.19	< 0.0001	Significant	22.39
Residual	0.75	21	0.036				
Lack of Fit	0.7	17	0.041	3.02	0.1468	Not significant	
Pure Error	0.054	4	0.014				
Cor Total	3.84	28					
Std. Dev. 0.19 R-Squared 0.8045 Mean 1.51 Adj R-Squared 0.7393 C.V. 12.55 Pred R-Squared 0.5121 PRESS 1.87 Adeq Precision 14.932							
Legend: A- Pulse on time, B- Pulse off time, C- Spark gap set voltage, D- Wire Feed Rate							

DESIGN-EXPERT Plot
Surface Roughness

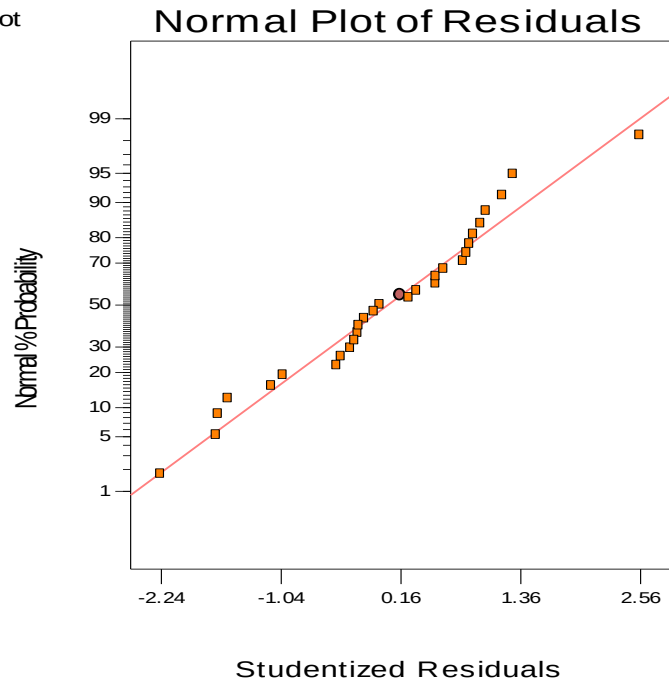


Figure 5.4 Normal probability plots of residuals for surface roughness

DESIGN-EXPERT Plot
Surface Roughness

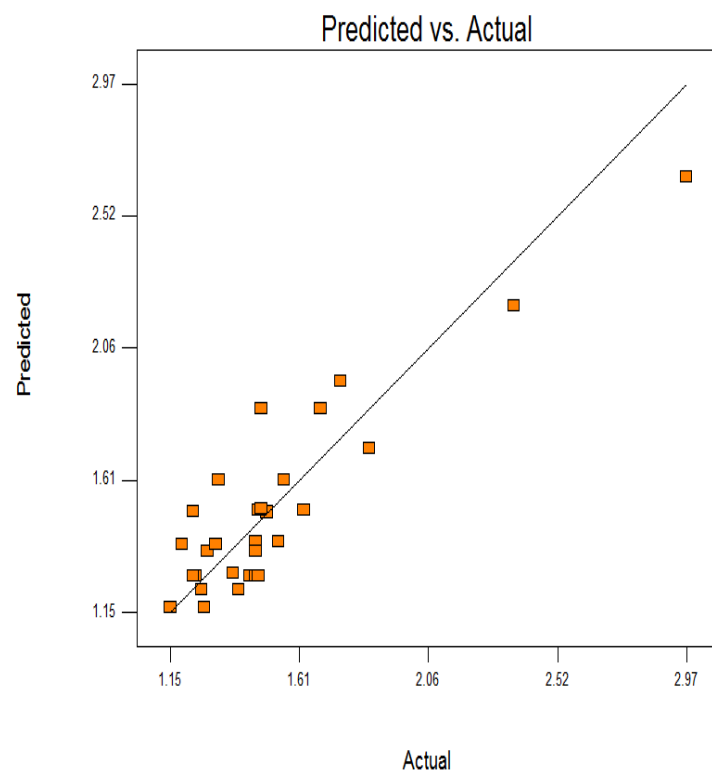


Figure 5.5 Plot of actual versus predicted of surface roughness

5.2.3.3 Analysis of variance and mathematical model for dimensional deviation

The term “dimensional deviation” is defined as the profile traced by wire and the job profile are not similar. The perpendicular distance between the actual profile and the profile traced by the wire is equal to half of the width of the cut [Sarkar et al., 2005]. Thus, the actual job produced is either undersized or oversized depending upon the job is punch or die. Table 5.9 show analysis of variance (ANOVA) intended for the quadratic model at 95% confidence level which is acquired by elimination of non significant terms by backward elimination technique. It demonstrates that F-value of the model is 18.68 and corresponding p-value is under 0.001, indicating that quadratic model is significant at 95% confidence level. Lack of fit of 0.8611 with p-value 0.48 suggests that it is not significant in respect to pure error. Additionally, predicted R^2 of 0.7852 is in reasonable agreement with adjusted R^2 of 0.8632, which demonstrates a high correlation amongst's observed and predicted values.

Subsequent response surface equation defining relation among surface roughness and process parameters in actual factors is obtained.

Dimensional Deviation = +12.00238 - 0.20123 * Pulse on time + 0.00937 * Pulse off time + 0.015970 * Spark gap voltage - 0.46958* Wire Feed +0.000966 * Pulse on time² + 0.000816 * Pulse off time² -0.000133* Spark gap voltage² – 0.0008 * Pulse on time * Pulse off time + 0.0045 * Pulse on time * Wire Feed -0.000875 * Spark gap voltage * Wire Feed

(5.3)

Table 5.9 ANOVA for response surface of reduced quadratic model of dimensional deviation

Source	Sum of Square s	DF	Mean Square	F Value	Prob > F	Remarks	% Contribution																
Model	0.028	10	0.00279	18.68	< 0.0001	Significant																	
A	0.00368	1	0.00368	24.61	0.0001	Significant	11.87																
B	0.0003	1	0.0003	2.01	0.1735	Not significant	0.96																
C	0.00368	1	0.00368	24.61	0.0001	Significant	11.87																
D	0.00083	1	0.00083	5.58	0.0296	Significant	2.67																
A ²	0.00393	1	0.00393	26.28	< 0.0001	Significant	12.67																
B ²	0.0028	1	0.0028	18.76	0.0004	Significant	9.03																
C ²	0.0012	1	0.0012	8.02	0.011	Significant	3.87																
AB	0.0016	1	0.0016	10.71	0.0042	Significant	5.16																
AD	0.0081	1	0.0081	54.24	< 0.0001	Significant	26.12																
CD	0.00123	1	0.00123	8.2	0.0103	Significant	3.96																
Residual	0.00269	18	0.00015																				
Lack of Fit	0.00169	14	0.00012	0.48	0.8611	Not significant																	
Pure Error	0.001	4	0.00025																				
Cor Total	0.031	28																					
<table><tr><td>Std. Dev.</td><td>0.012</td><td>R-Squared</td><td>0.9121</td></tr><tr><td>Mean</td><td>0.047</td><td>Adj R-Squared</td><td>0.8632</td></tr><tr><td>C.V.</td><td>25.87</td><td>Pred R-Squared</td><td>0.7852</td></tr><tr><td>PRESS</td><td>0.00656</td><td>Adeq Precision</td><td>17.936</td></tr></table>								Std. Dev.	0.012	R-Squared	0.9121	Mean	0.047	Adj R-Squared	0.8632	C.V.	25.87	Pred R-Squared	0.7852	PRESS	0.00656	Adeq Precision	17.936
Std. Dev.	0.012	R-Squared	0.9121																				
Mean	0.047	Adj R-Squared	0.8632																				
C.V.	25.87	Pred R-Squared	0.7852																				
PRESS	0.00656	Adeq Precision	17.936																				
Legend: A- Pulse on time, B- Pulse off time, C- Spark gap set voltage, D- Wire Feed Rate																							

DESIGN-EXPERT Plot
Dimensional Deviation

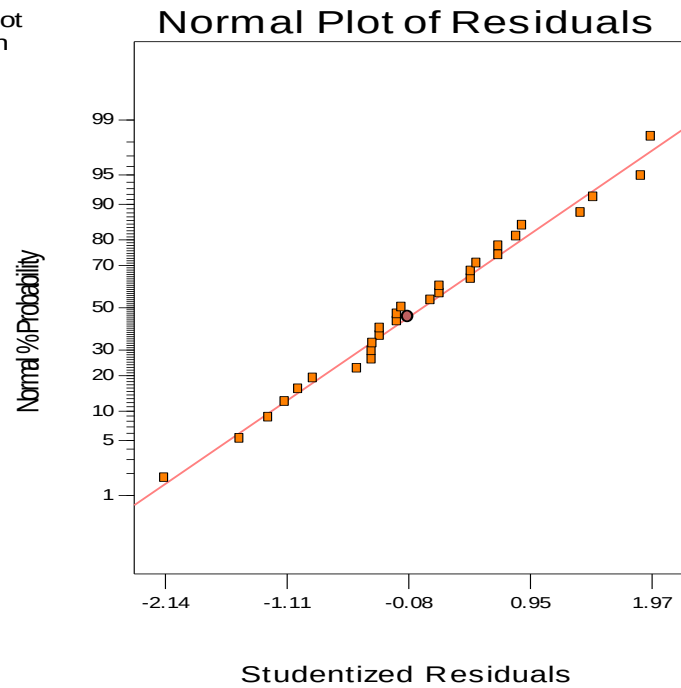


Figure 5.6 Normal probability plots of residuals for dimensional deviation

DESIGN-EXPERT Plot
Dimensional Deviation

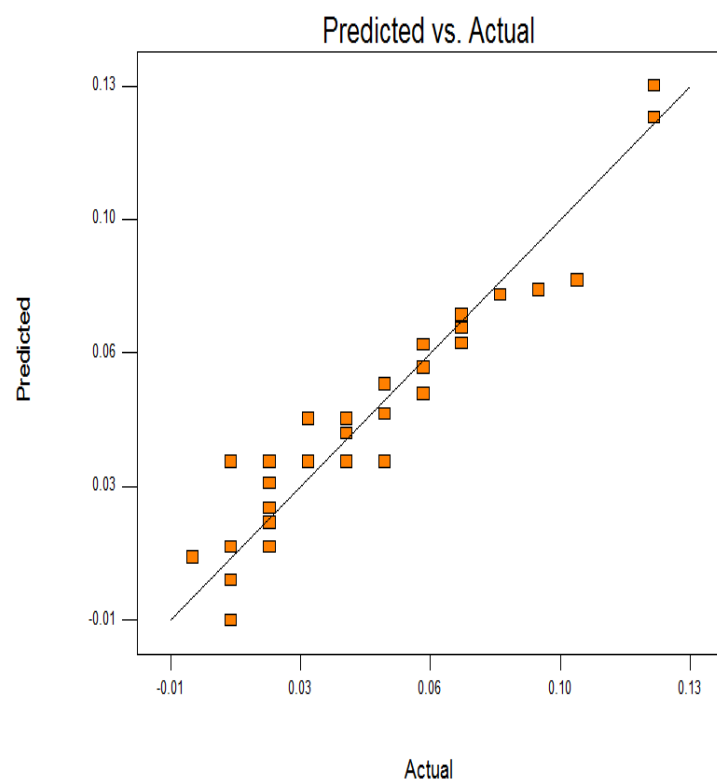


Figure 5.7 Plot of actual versus predicted of dimensional deviation

5.2.4 For Cryogenated wire

5.2.4.1 Analysis of variance and mathematical model for cutting speed

Table 5.10 demonstrates that analysis of variance (ANOVA) for the quadratic model at 95% confidence level which is acquired by eliminating non significant terms by backward elimination. It demonstrates that F-value of the model is 161.25 and corresponding p-value is under 0.001, showing that quadratic model is significant at 95% confidence level. Lack of fit of 0.3130 with p-value 1.75 implies that it is not significant in respect to pure error. Additionally, predicted R^2 of 0.9566 is in reasonable agreement with adjusted R^2 of 0.9786, which demonstrates a high correlation among observed and predicted values.

Figure 5.8-5.9 shows normal probability plot of residuals for cutting speed and plot of actual versus predicted of cutting speed. A check on the plot reveals that residuals are clustered near to straight line, which means that errors are normally distributed and regression model is reasonably well fitted with observed values. The adequate precision is 46.614; it recommends that quadratic model can be used to find the way in the design space.

The regression equation for the dimensional deviation(DD) has been modeled as follows:

$$\begin{aligned} \text{Cutting Speed} = & -0.79672 - 0.055341 * \text{Pulse on time} + 0.10676 * \text{Pulse off time} + \\ & 0.035167 * \text{Spark gap voltage} + 0.001334 * \text{Pulse on time}^2 + 0.001634 * \text{Pulse off time}^2 \\ & - 0.0032 * \text{Pulse on time} * \text{Pulse off time} - 0.00105 * \text{Pulse on time} * \text{Spark gap voltage} \\ & + 0.00135 * \text{Pulse off time} * \text{Spark gap voltage} \end{aligned}$$

(5.4)

Table 5.10 ANOVA for response surface of reduced quadratic model of cutting speed

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	Remarks	% Contribution
Model	1.2	8	0.15	161.25	< 0.0001	Significant	
A	0.46	1	0.46	491.96	< 0.0001	Significant	37.7
B	0.28	1	0.28	297.6	< 0.0001	Significant	22.95
C	0.39	1	0.39	423.07	< 0.0001	Significant	31.96
A ²	0.00768	1	0.00768	8.28	0.0093	Significant	0.62
B ²	0.012	1	0.012	12.42	0.0021	Significant	0.98
AB	0.026	1	0.026	27.6	< 0.0001	Significant	2.13
AC	0.011	1	0.011	11.89	0.0025	Significant	0.9
BC	0.018	1	0.018	19.65	0.0003	Significant	1.47
Residual	0.019	20	0.00093				
Lack of Fit	0.016	16	0.00101	1.75	0.313	Not significant	
Pure Error	0.00232	4	0.00058				
Cor Total	1.22	28					
Std. Dev. 0.030 R-Squared 0.9847 Mean 0.63 Adj R-Squared 0.9786 C.V. 4.82 Pred R-Squared 0.9566 PRESS 0.053 Adeq Precision 46.614							
Legend: A- Pulse on time, B- Pulse off time, C- Spark gap set voltage, D- Wire Feed Rate							

DESIGN-EXPERT Plot
Cutting Speed

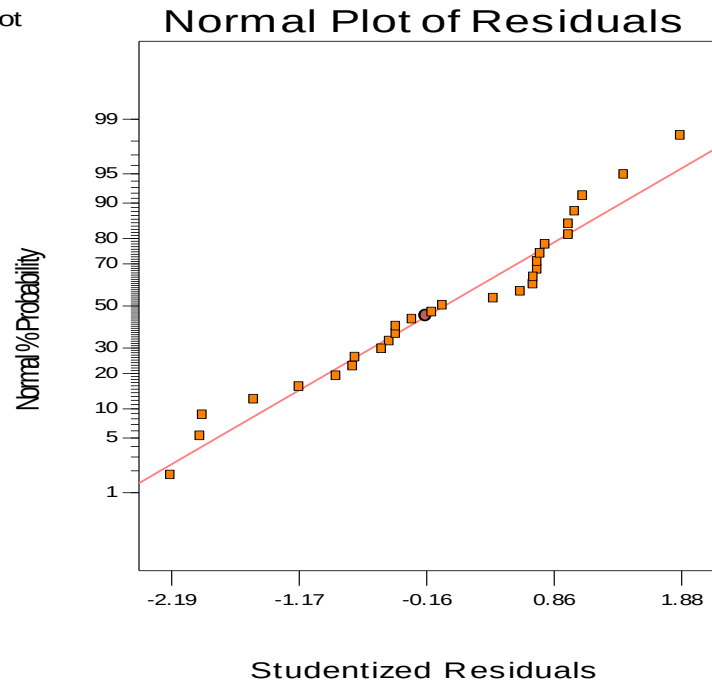


Figure 5.8 Normal probability plots of residuals for cutting speed

DESIGN-EXPERT Plot
Cutting Speed

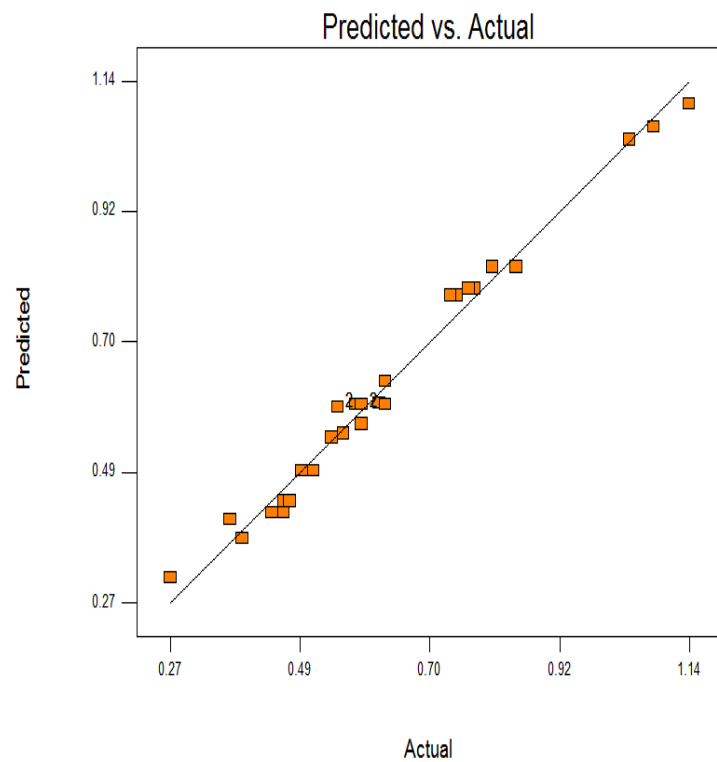


Figure 5.9 Plot of actual versus predicted of cutting speed

5.2.4.2 Analysis of variance and mathematical model for surface roughness

Adequacy of the model is checked using ANOVA as shown in Table 5.11. It demonstrates that F-value of the model is 20.55 and corresponding p-value is under 0.0001. Thus, quadratic model is significant at 95% confidence level. The p-value of lack of fit is greater than 0.05. Thus, lack of fit is insignificant. Moreover, lack of fit value of 0.7750 suggests that it is not significant in respect to pure error. Further, predicted R^2 of 0.7717 is in reasonable agreement with adjusted R^2 of 0.8747 and it demonstrates a high correlation among observed values and predicted values. Figure 5.10 shows normal probability plot of residuals for surface roughness. It clearly display that errors are normally distributed as most of the residuals are clustered around the straight line. The plot of observed versus predicted values as presented in Figure 5.11 indicate that observed response are closer to the predicted values and model can define actual relationship among process parameters and output. Adequate precision value is 21.657 and it demonstrates that quadratic model can be used to find the way in the design space.

The regression model for surface roughness is given as :

$$\begin{aligned} \text{Surface roughness} = & +19.43167 - 1.00367 * \text{Pulse on time} + 0.94850 * \text{Pulse off time} \\ & +0.55367 * \text{Spark gap voltage} + 0.27625 * \text{Wire Feed} + 0.007016 * \text{Pulse on time}^2 - \\ & 0.00308 * \text{Pulse off time}^2 + 0.001141 \text{ Spark gap voltage}^2 - 0.028333 * \text{Wire Feed}^2 - \\ & 0.0057 * \text{Pulse on time} * \text{Pulse off time} - 0.00585 * \text{Pulse on time} * \text{Spark gap voltage} \end{aligned} \quad (5.5)$$

Table 5.11 ANOVA for response surface of reduced quadratic model of surface roughness

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	Remarks	% Contribution
Model	1.34	10	0.13	20.55	< 0.0001	Significant	
A	0.32	1	0.32	49.21	< 0.0001	Significant	22.06
B	0.071	1	0.071	10.84	0.004	Significant	4.89
C	0.029	1	0.029	4.46	0.049	Significant	2
D	0.00241	1	0.00241	0.37	0.5505	Not significant	0.16
A ²	0.2	1	0.2	30.68	< 0.0001	Significant	13.79
B ²	0.039	1	0.039	5.92	0.0256	Significant	2.68
C ²	0.085	1	0.085	13	0.002	Significant	5.86
D ²	0.083	1	0.083	12.81	0.0021	Significant	5.72
AB	0.081	1	0.081	12.49	0.0024	Significant	5.58
AC	0.34	1	0.34	52.61	< 0.0001	Significant	23.44
Residual	0.12	18	0.00651				
Lack of Fit	0.08	14	0.00572	0.62	0.775	Not significant	
Pure Error	0.037	4	0.00925				
Cor Total	1.45	28					
Std. Dev. 0.081 R-Squared 0.9195 Mean 1.36 Adj R-Squared 0.8747 C.V. 5.93 Pred R-Squared 0.7717 PRESS 0.33 Adeq Precision 21.657							
Legend: A- Pulse on time, B- Pulse off time, C- Spark gap set voltage, D- Wire Feed Rate							

DESIGN-EXPERT Plot
Surface Roughness

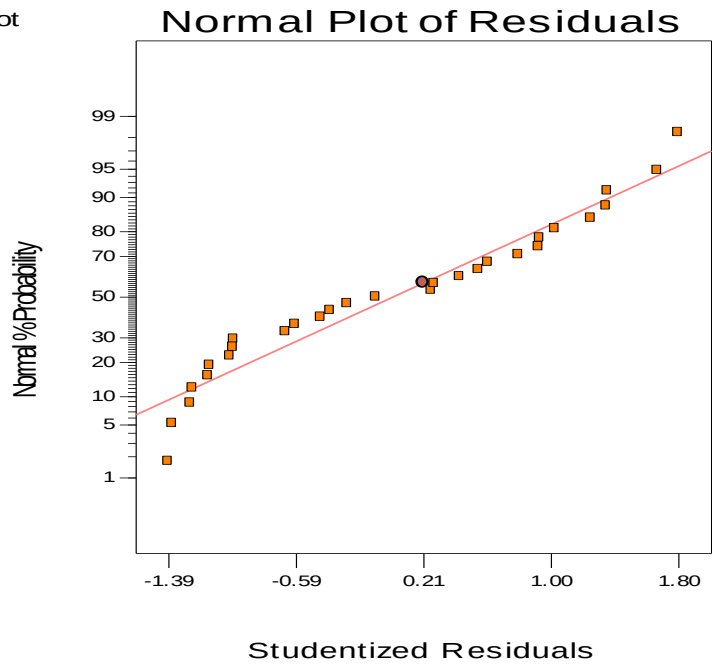


Figure 5.10 Normal probability plots of residuals for surface roughness

DESIGN-EXPERT Plot
Surface Roughness

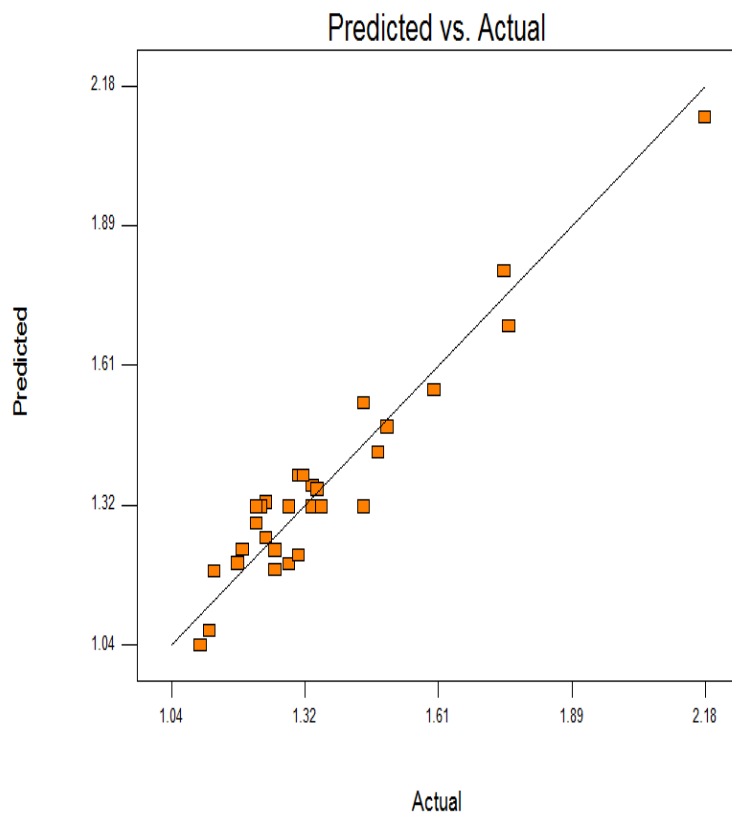


Figure 5.11 Plot of actual versus predicted of surface roughness

5.2.4.3 Analysis of variance and mathematical model for dimensional deviation

The ANOVA table for cryogenated experiment for dimensional deviation on M42 HSS is shown in table. The punches of length 10mm, breadth 10mm and thickness 12 mm are cut using cryogenated wire. The dimensional deviation of the 29 such pieces is noted down and the ANOVA is done using DOE. The data is normally distributed. It is observed that all the experimental results are approximately very close to the predicted values (Figures 5.12-5.13). The model F-value 18.68 implies that model is significant. There is only a 0.01% chance that a “Model F-Value” this large could occur due to noise. The “Lack of fit F-value” of 0.48 implies that lack of fit is not significant relative to the pure error. The “Pred R-Squared” of 0.7852 is in reasonable agreement with the “Adj R-Squared” of 0.8632. “Adeq Precision” measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio is 17.936 indicates an adequate signal and it demonstrates that quadratic model can be utilized to find the way in the design space. The regression equation for the dimensional deviation(DD) was modeled as follows:

$$\begin{aligned} \text{Dimensional deviation(DD)} = & +12.00238 - 0.20123 * \text{Pulse on time} + 0.009378 * \text{Pulse} \\ & \text{off time} + 0.015970 * \text{Spark gap voltage} - 0.46958 * \text{Wire Feed} + 0.000966 * \text{Pulse on} \\ & \text{time}^2 + 0.000816 * \text{Pulse off time}^2 - 0.000133 * \text{Spark gap voltage}^2 - 0.0008 * \text{Pulse on} \\ & \text{time} * \text{Pulse off time} + 0.0045 * \text{Pulse on time} * \text{Wire Feed} - 0.000875 * \text{Spark gap} \\ & \text{voltage} * \text{Wire Feed} \end{aligned} \quad (5.6)$$

Figure 5.13 indicates that the predicted values have slight variation around the central line the plot could justify the ability of the model to predict the response with reasonable accuracy.

Table 5.12 ANOVA for response surface of reduced quadratic model of dimensional deviation

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	Remarks	% Contribution
Model	0.028	10	0.00279	18.68	< 0.0001	Significant	
A	0.00368	1	0.00368	24.61	0.0001	Significant	11.87
B	0.0003	1	0.0003	2.01	0.1735	Not significant	0.96
C	0.00368	1	0.00368	24.61	0.0001	Significant	11.87
D	0.00083	1	0.00083	5.58	0.0296	Significant	2.67
A ²	0.00393	1	0.00393	26.28	< 0.0001	Significant	12.67
B ²	0.0028	1	0.0028	18.76	0.0004	Significant	9.03
C ²	0.0012	1	0.0012	8.02	0.011	Significant	3.87
AB	0.0016	1	0.0016	10.71	0.0042	Significant	5.16
AD	0.0081	1	0.0081	54.24	< 0.0001	Significant	26.12
CD	0.00123	1	0.00123	8.2	0.0103	Significant	3.96
Residual	0.00269	18	0.00015				
Lack of Fit	0.00169	14	0.00012	0.48	0.8611	Not significant	
Pure Error	0.001	4	0.00025				
Cor Total	0.031	28					
Std. Dev. 0.012 R-Squared 0.9121 Mean 0.047 Adj R-Squared 0.8632 C.V. 25.87 Pred R-Squared 0.7852 PRESS 6.568E-003 Adeq Precision 17.936							
Legend: A- Pulse on time, B- Pulse off time, C- Spark gap set voltage, D- Wire Feed Rate							

DESIGN-EXPERT Plot
Dimensional Deviation

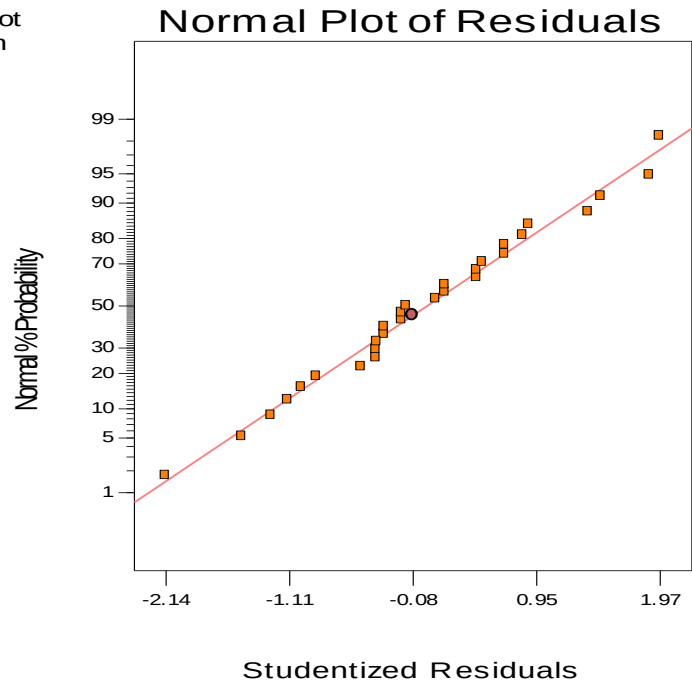


Figure 5.12 Normal probability plots of residuals for dimensional deviation

DESIGN-EXPERT Plot
Dimensional Deviation

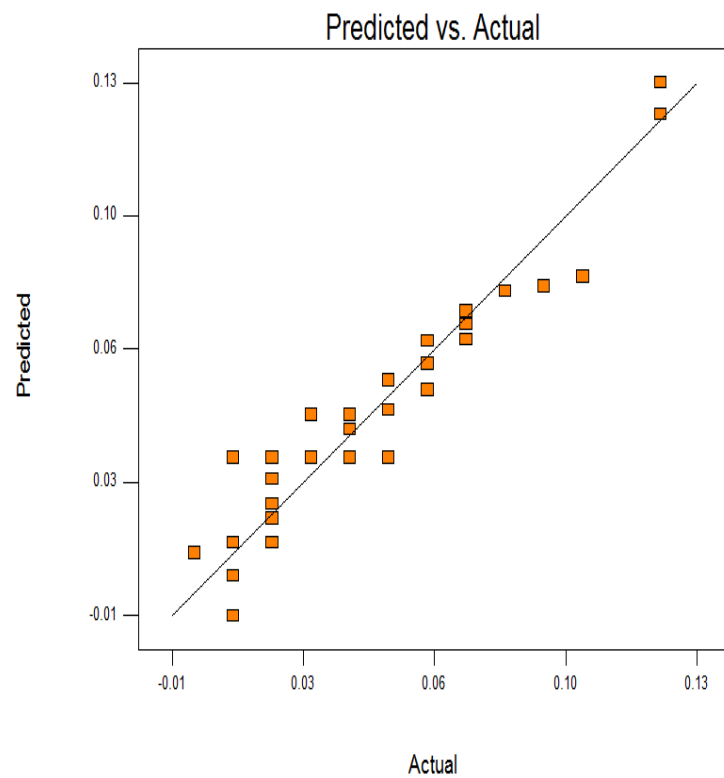


Figure 5.13 Plot of actual versus predicted of dimensional deviation

5.3 EFFECT OF PROCESS PARAMETERS ON RESPONSE CHARACTERISTICS

This segment presents the impact of process parameters on response characteristics i.e. cutting speed, surface roughness and dimensional deviation . It examines individual and in addition the interaction effects of different parameters on considered response characteristics. The impact of different parameters on various response characteristics is given in following sub sections.

5.3.1 FOR UNTREATED OR NON CRYOGENATED PIECES

5.3.1.1 Effect of process parameters on cutting speed

The main effect plots in Figures from 5.14 to 5.20 shows that the cutting speed was essentially influenced by T_{on} , T_{off} , SV and WF. Cutting speed is increased appreciably from 0.35 to 0.77 mm/min as pulse on time was increased from 110mu to 120mu. This is because of the fact that higher value of pulse on time increases the span of discharge energy and it results into rapid melting and evaporation of material. Accordingly, substantial pieces of material are removed and subsequently, increment in cutting rate is acquired. The present result is in accordance with the result acquired in former studies [Tarang et al. 1995; Sarkar et al. 2006].

In the interim, by decreasing the pulse off time and spark gap voltage, the machining rate appreciably improved. Enlarged span of pulse off time decrease the number of discharges inside a given period. Subsequently, less discharge energy is encroached on the work piece in a given time that lessens the rate of metal disintegration, in this manner decreasing the cutting speed [Saha et al. 2009]. Since pulse on time and pulse off time demonstrated the higher percentage contribution when contrasted with the other two factors (spark gap voltage and wire feed), they can be viewed as most significant to the cutting speed. Every cycle has an on-time and off-time that is communicated in mu(machine unit). Taking into account the trends of influence (Figures 5.14-5.20), maximum cutting speed can be attained when the parameters are set at; T_{on} = 120 mu, T_{off} = 50 mu, SV= 50V and WF = 5m/min.

Three interactions have been found to be considerable $T_{on} \times T_{off}$, $T_{on} \times SV$ and $T_{on} \times WF$ as shown in Figures from 5.18 to 5.20.

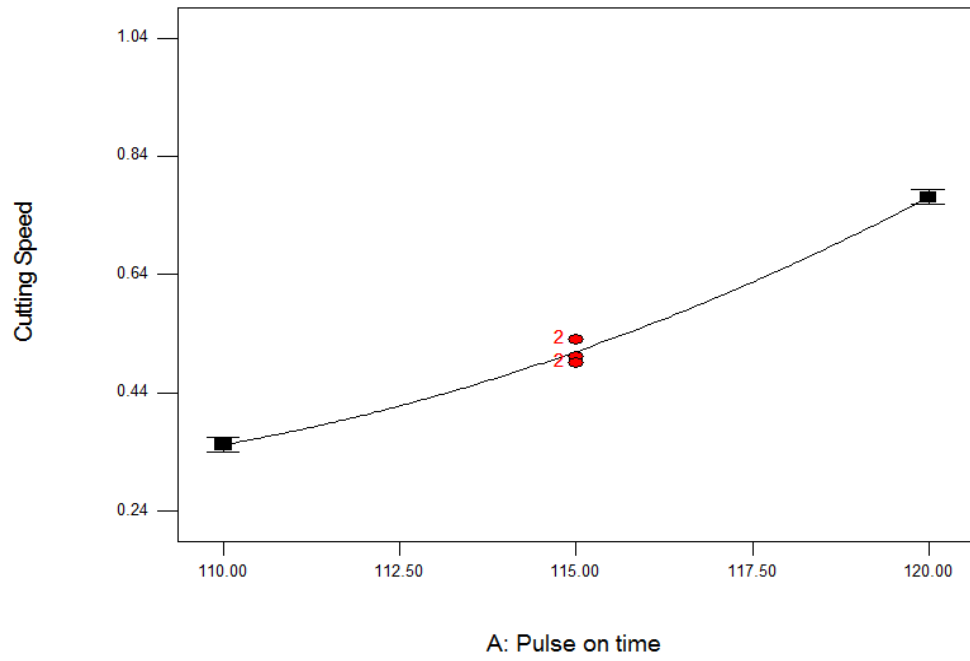


Figure 5.14 Effect of pulse on time on cutting speed

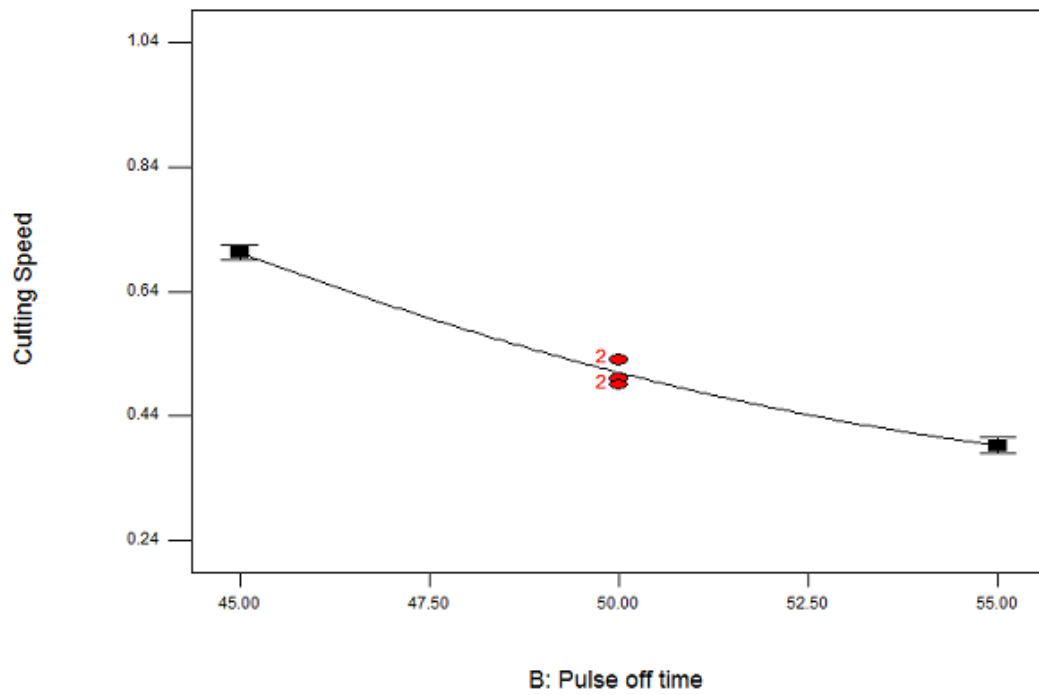


Figure 5.15 Effect of pulse off time on cutting speed

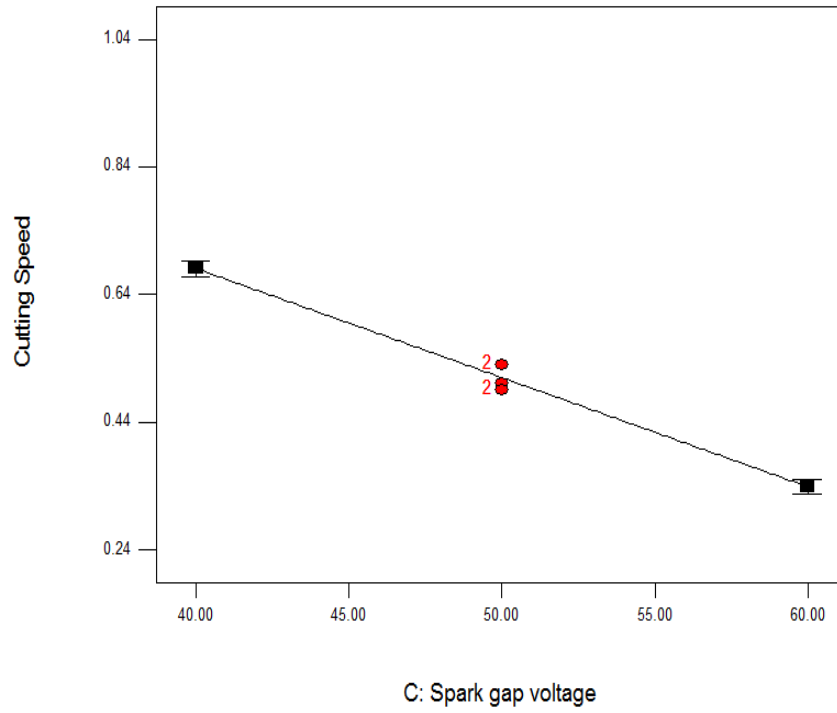


Figure 5.16 Effect of Spark gap voltage on cutting speed

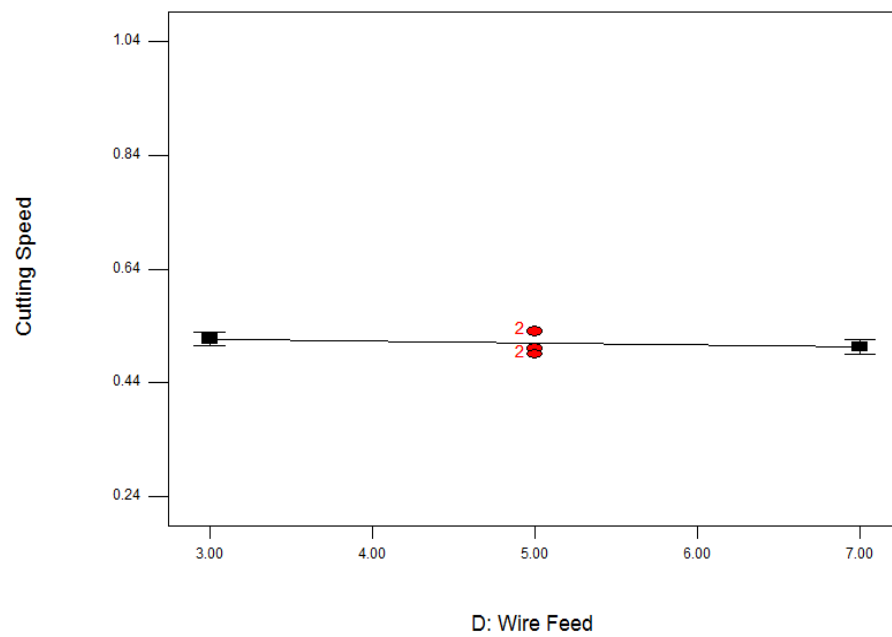


Figure 5.17 Effect of wire feed on cutting speed

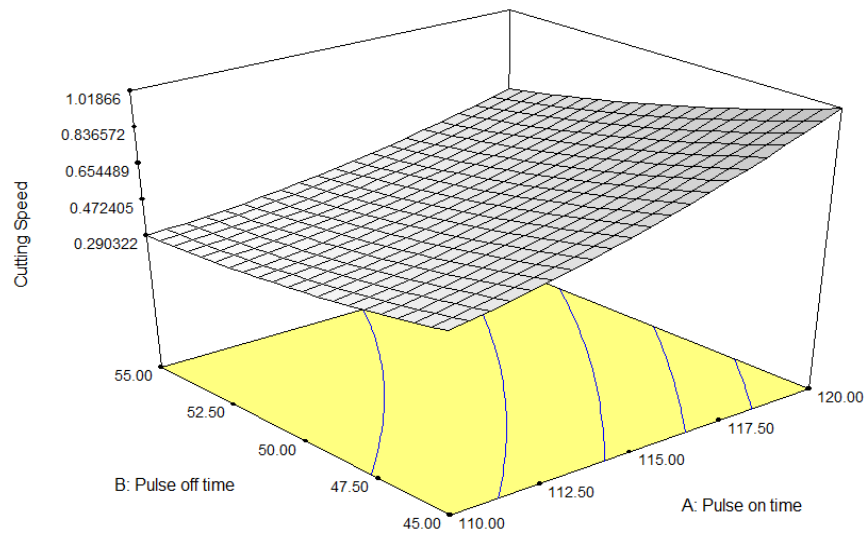


Figure 5.18 Interaction plot between pulse on time and pulse off for cutting speed

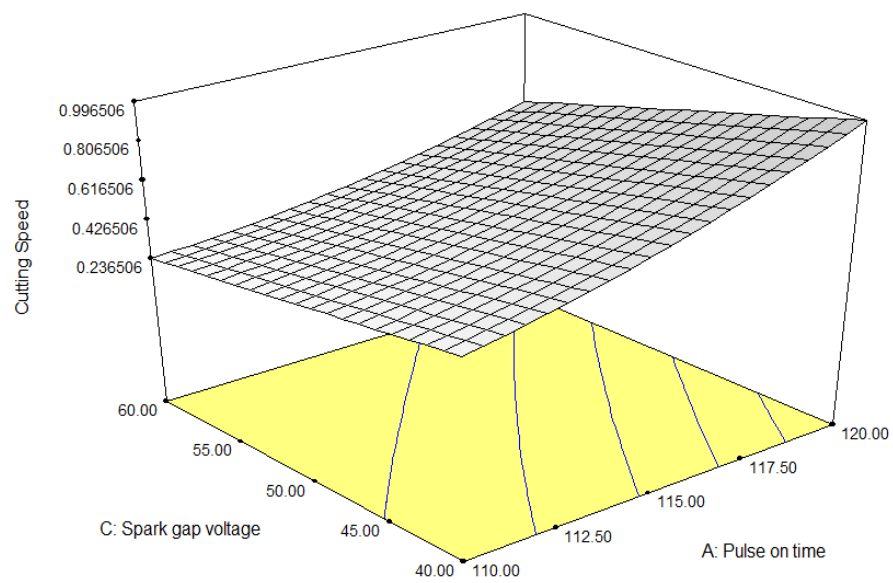


Figure 5.19 Interaction plot between pulse on time and spark gap voltage for cutting speed

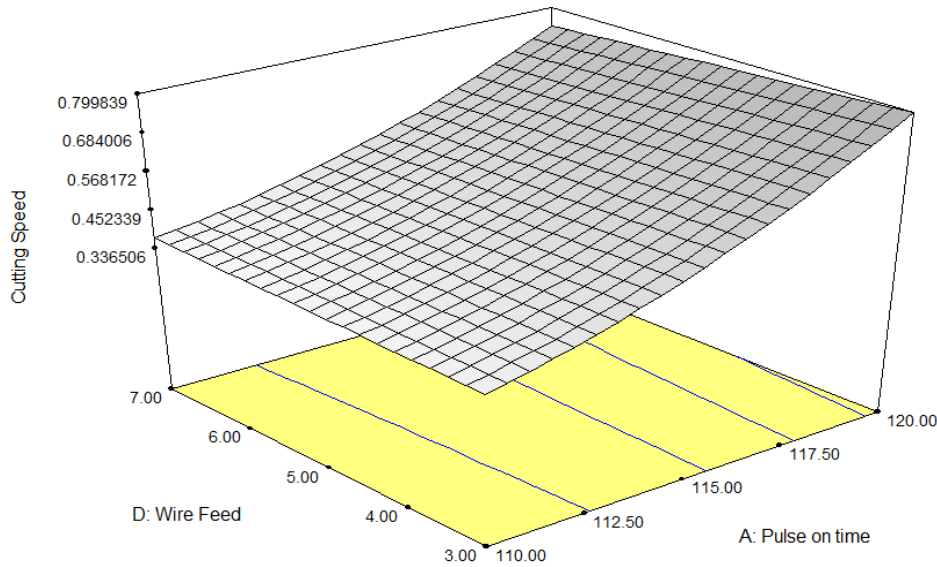


Figure 5.20 Interaction plot between pulse on time and wire feed for cutting speed

5.3.1.2 Effect of process parameters on surface roughness

Taking into account analysis of variance, the impact of T_{on} , T_{off} , SV and wire feed(WF) is revealed for surface roughness. From the major effect plots, figures from 5.21 to 5.24, it was noticed that as the pulse on time is expanded the surface roughness increased considerably with value of 1.36 to 1.85 μm . The longer the spark is maintained, more is the material evacuation. Subsequently the resulting craters and holes will be more extensive and more profound; therefore surface roughness increases.

When pulse on time was expanded from 110 to 120 μm (machining units), the surface roughness increased from 1.36 to 1.85 μm (Figure 5.21). The surface roughness is mostly influenced by the amount of discharge energy which increases with increase in pulse on time. A large discharging energy will bring out violent sparks resulting in a deeper erosion crater on the surface. Going with the cooling process after the spilling of liquid metal, residues stay at the fringe of the crater to shape a rough surface. In the alternate words, double sparking or re-sparking can bring about poor surface finish since only the early phase sparks contributed to the material removal, while the following sparks were poorly distributed along the surface, debris and removed particles [Liao and Yu, 2003; Liu et al., 2009].

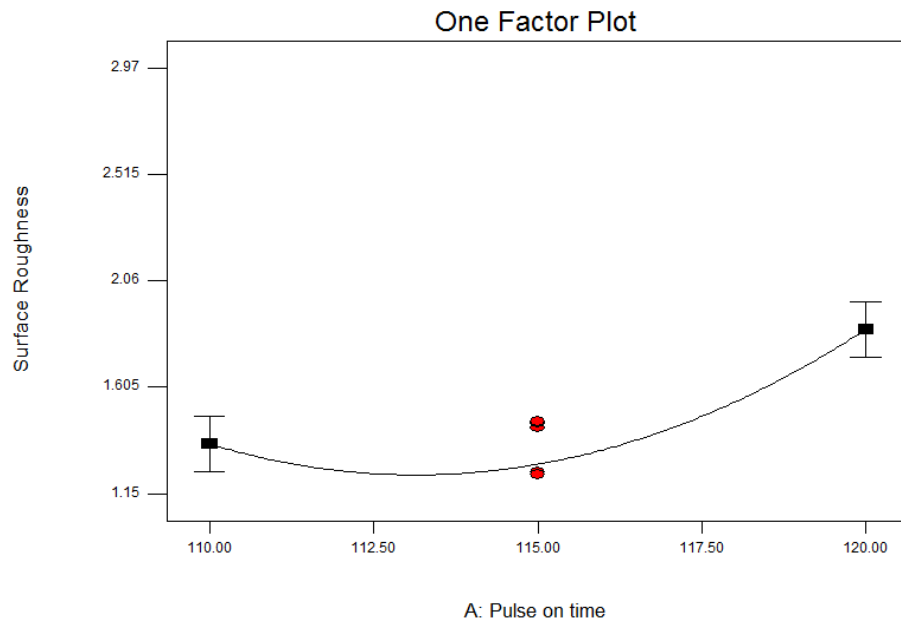


Figure 5.21 Effect of pulse on time on surface roughness

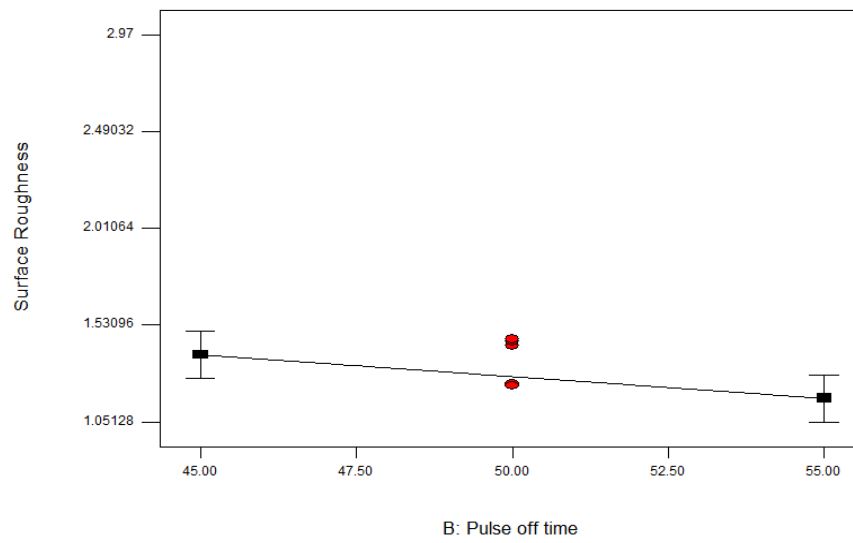


Figure 5.22 Effect of pulse off time on surface roughness

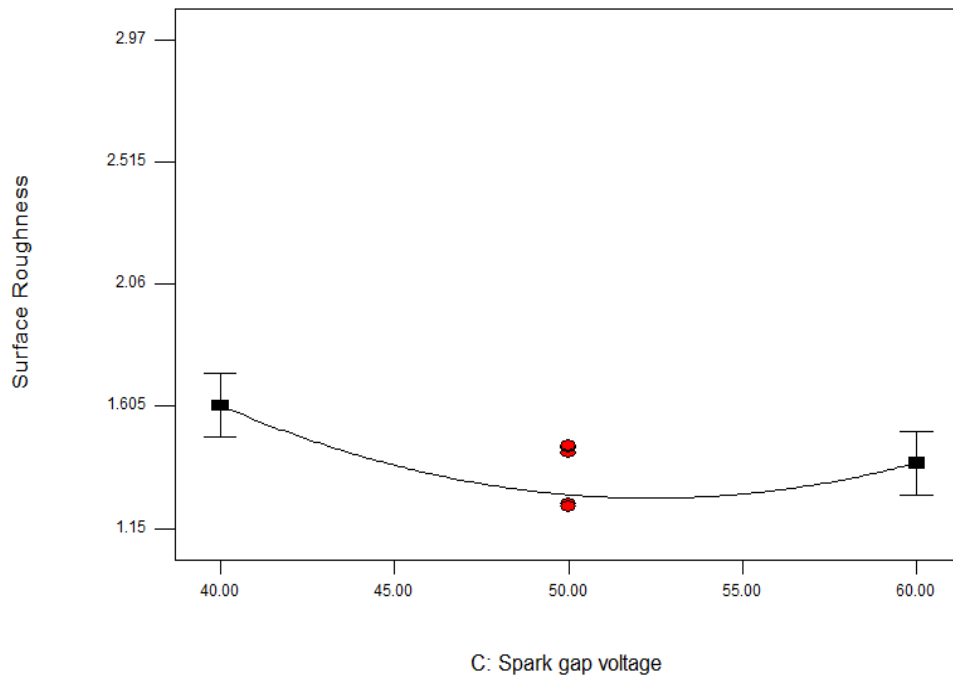


Figure 5.23 Effect of spark gap voltage on surface roughness

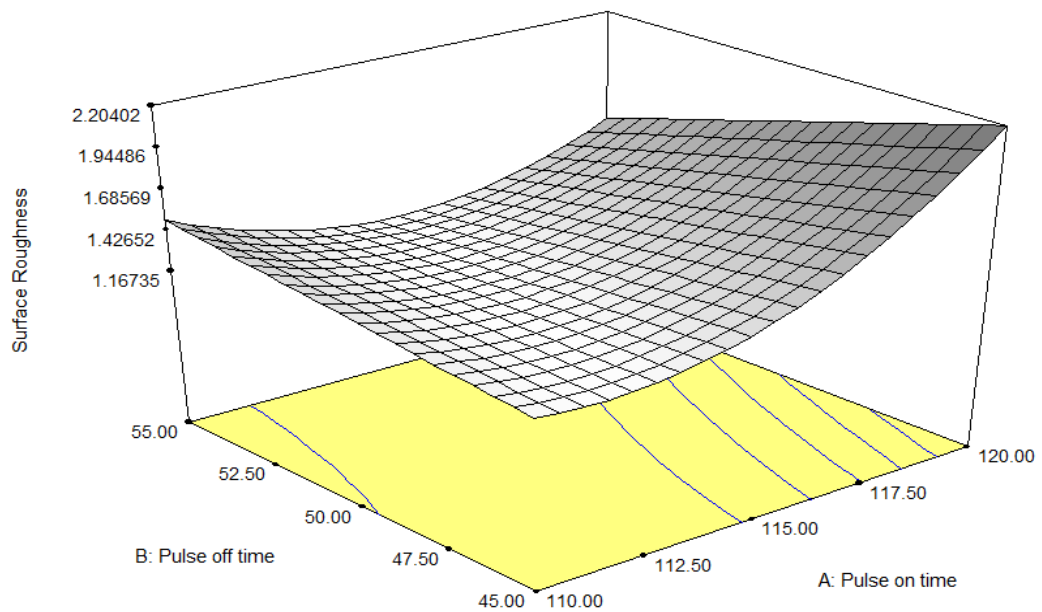


Figure 5.24 Interaction plot between pulse on time and pulse off for surface roughness

5.3.1.2 Effect of process parameters on dimensional deviation

The impacts of procedure parameters got from ANOVA i.e. Ton, Toff, SV and WF for dimensional deviation are displayed in this segment. From the fundamental impact plots in light of the figures from 5.25 to 5.29, it is watched that when pulse on time expanded,

the estimation of dimensional deviation likewise expanded essentially. The dimensional deviation is diminished from 0.038 to 0.0034 mm on expanding the spark crevice voltage from 40 volt to 60 volt. The dimensional deviation is observed to be altogether influenced by pulse on time and pulse off time components. A likely purpose behind it might be that with expansion in pulse on time, discharge energy increases. Amid each individual spark discharge, the wire encounters an effect that demonstrations in the opposite direction of the discharge occurrence course of the release event due to which dimensional deviation increases.

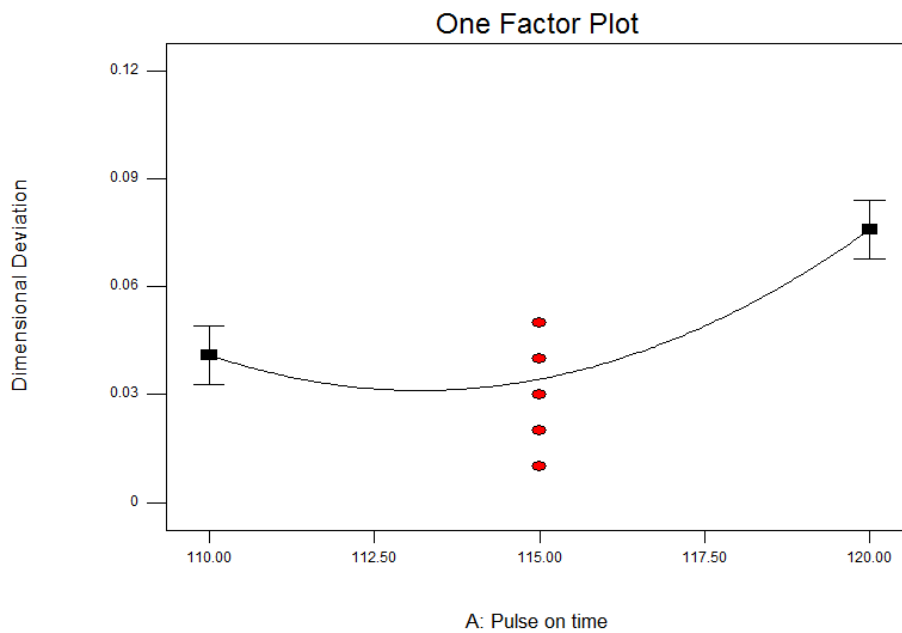


Figure 5.25 Effect of pulse on time on dimensional deviation

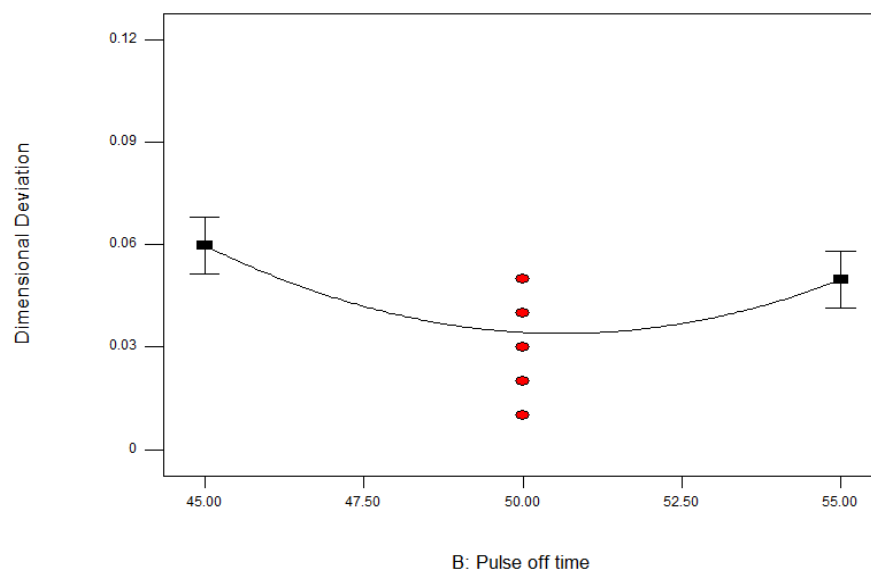


Figure 5.26 Effect of pulse off time on dimensional deviation

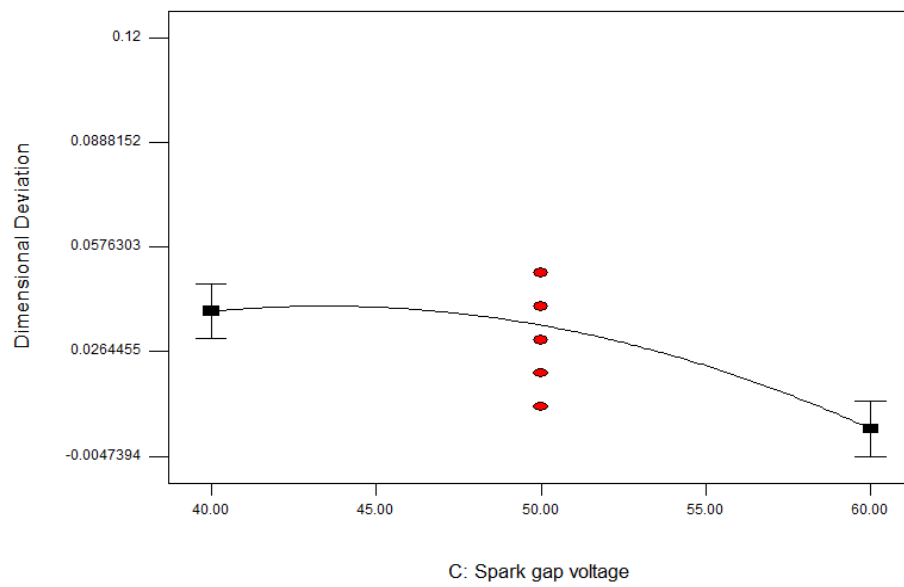


Figure 5.27 Effect of spark gap voltage on dimensional deviation

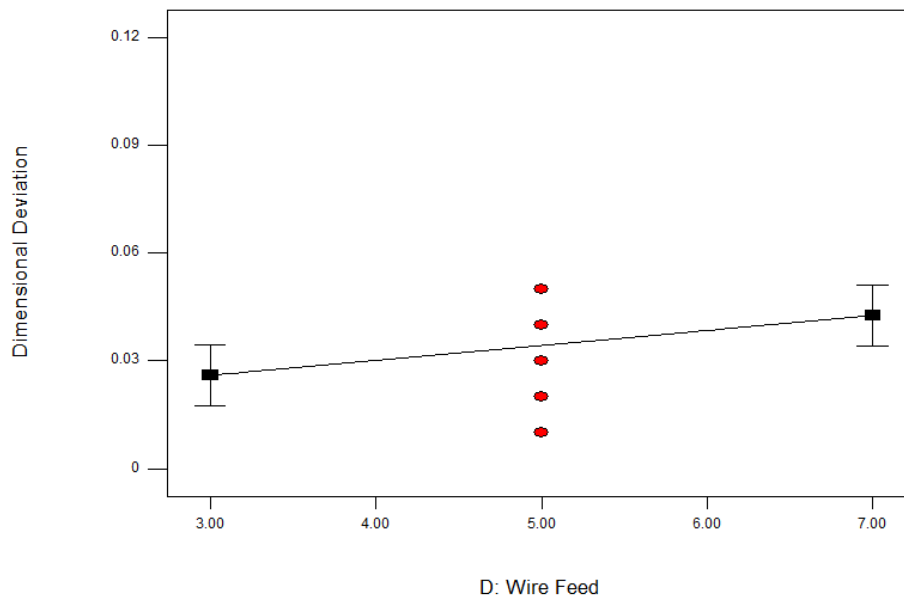


Figure 5.28 Effect of wire feed on dimensional deviation

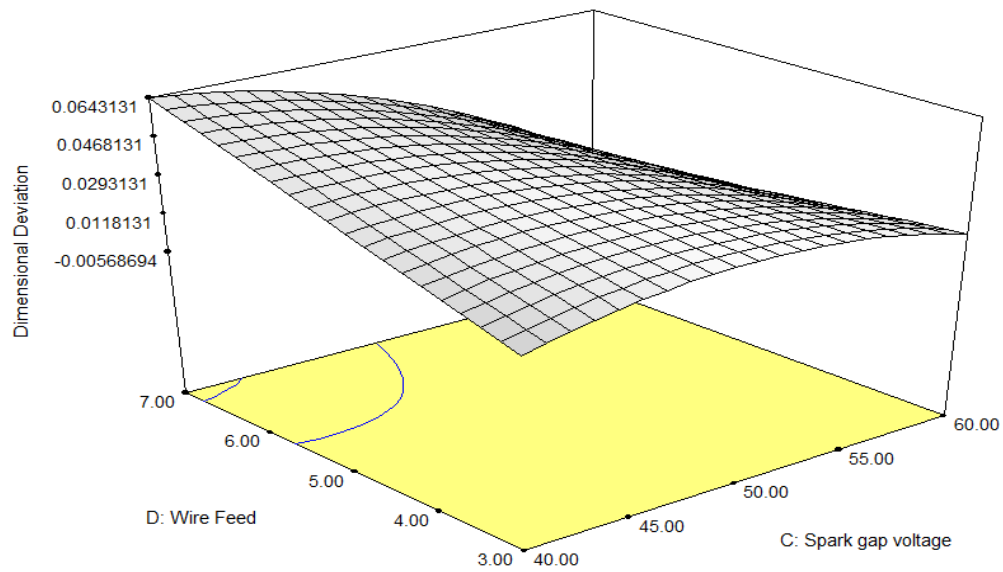


Figure 5.29 Interaction plot between spark gap voltage and wire tension for dimensional deviation

5.3.2 For Cryogenic treatment

5.3.2.1 Effect of process parameters on cutting speed

The ANOVA test summarizes the effects of process variables and the interactions for second order quadratic model for cutting speed.

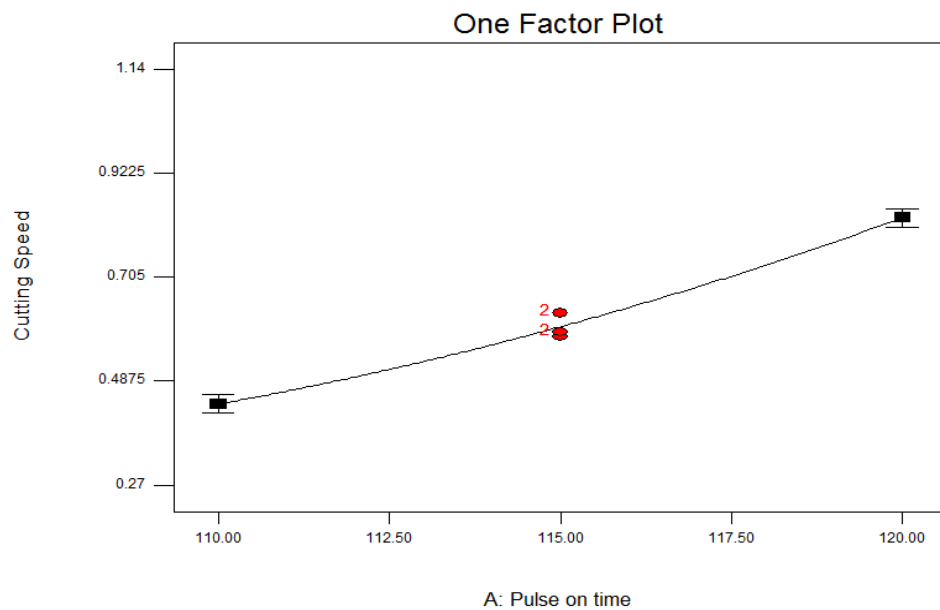


Figure 5.30 Effect of pulse on time on cutting speed

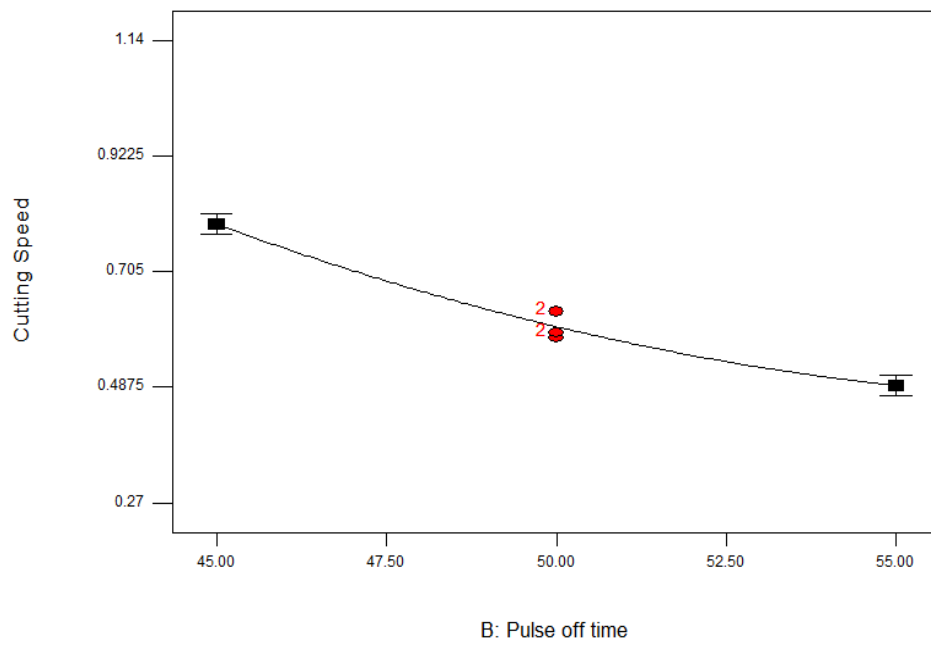


Figure 5.31 Effect of pulse off time on cutting speed

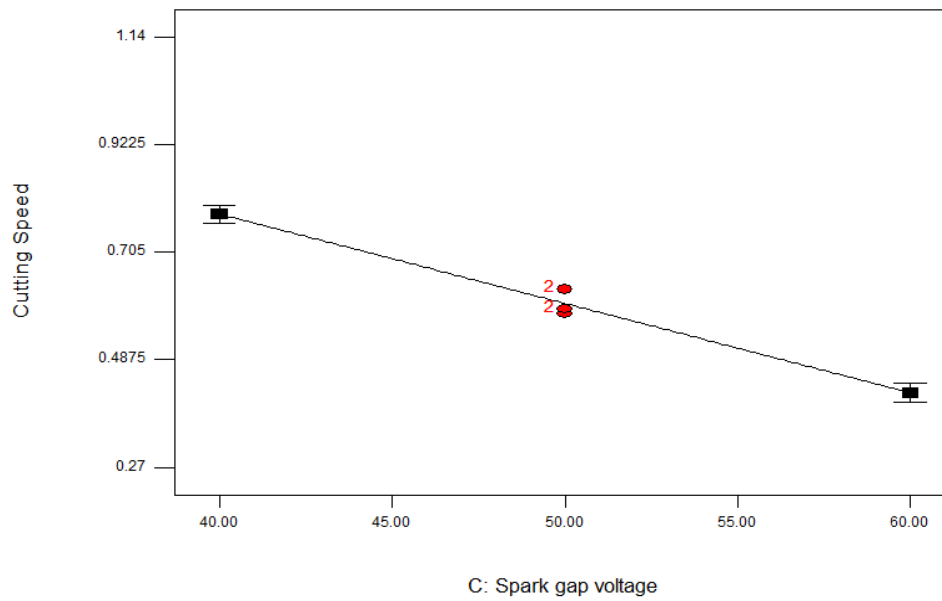


Figure 5.32 Effect of spark gap voltage on cutting speed

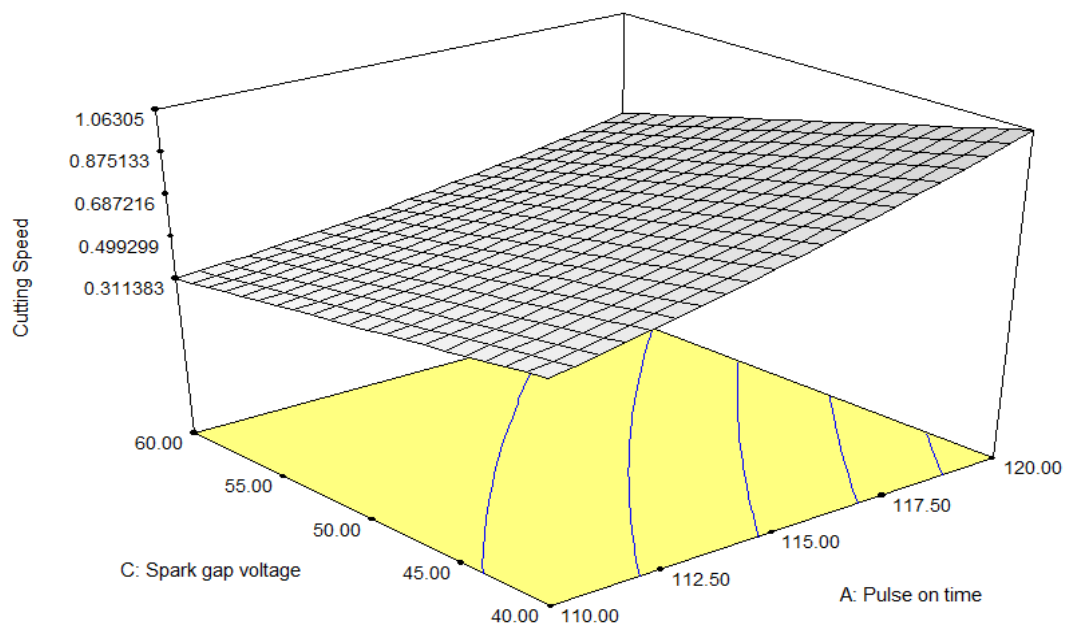


Figure 5.33 Interaction plot between spark gap voltage and the pulse on time for cutting speed

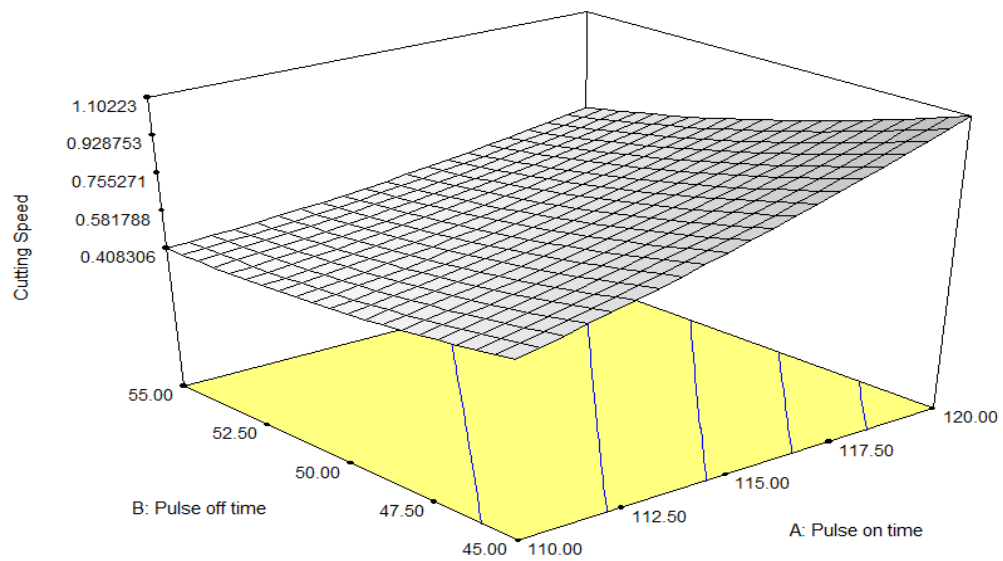


Figure 5.34 Interaction plot between peak current and pulse off time for cutting speed

5.3.2.2 Effect of process parameters on surface roughness

In light of analysis of variance, four input variables Ton, Toff, SV, wire feed and one interaction (Ton×SV) are noteworthy for surface roughness. From the principle impact plots as appeared in Figures from 5.35 to 5.39,

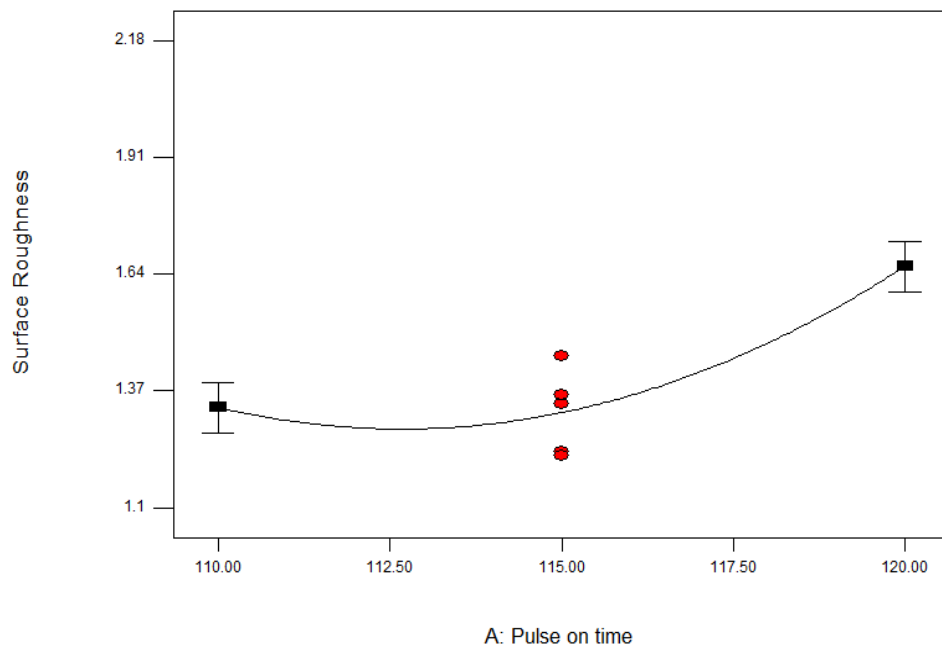


Figure 5.35 Effect of pulse on time on surface roughness

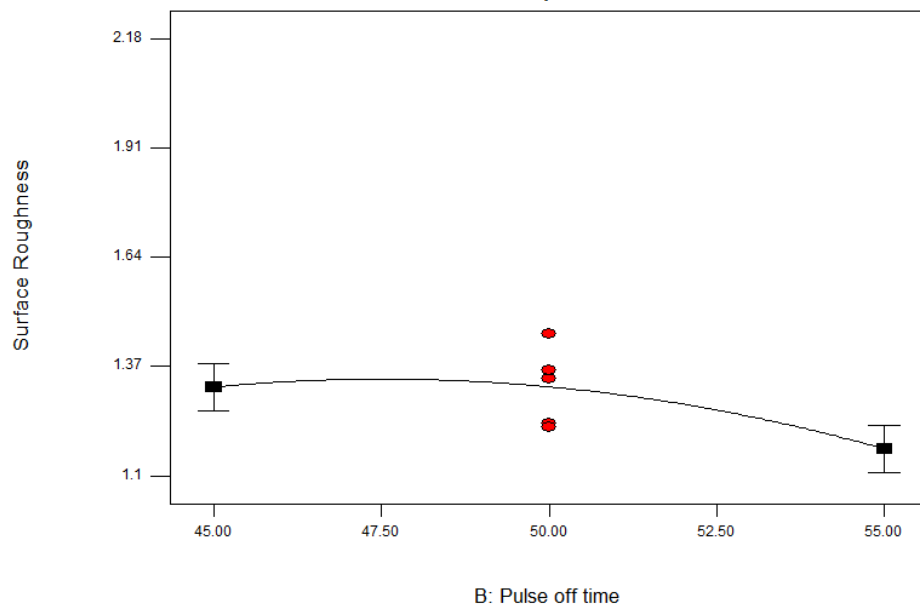


Figure 5.36 Effect of pulse off time on surface roughness

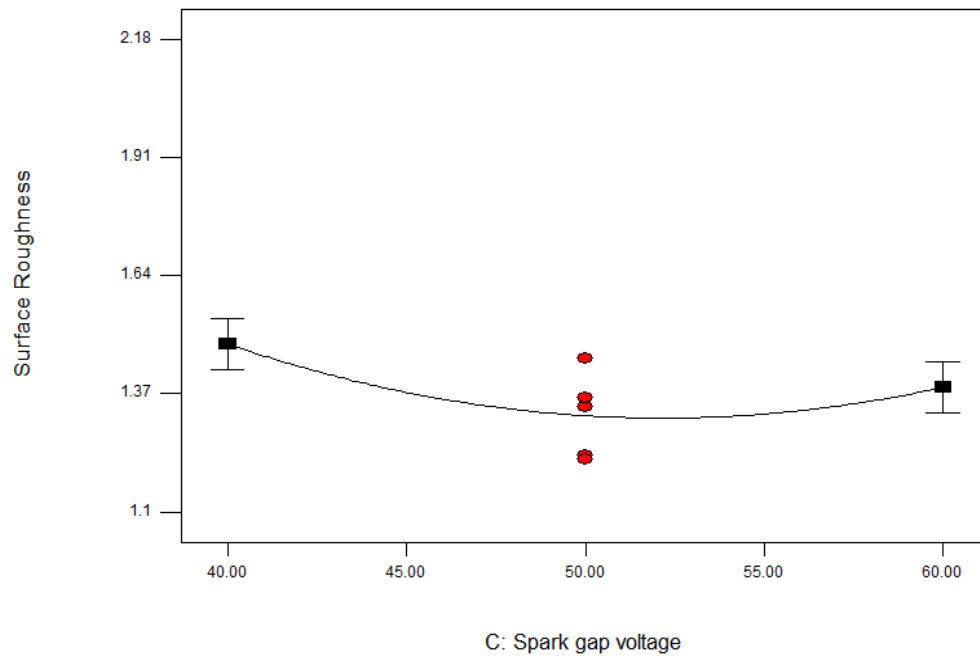


Figure 5.37 Effect of spark gap voltage on surface roughness

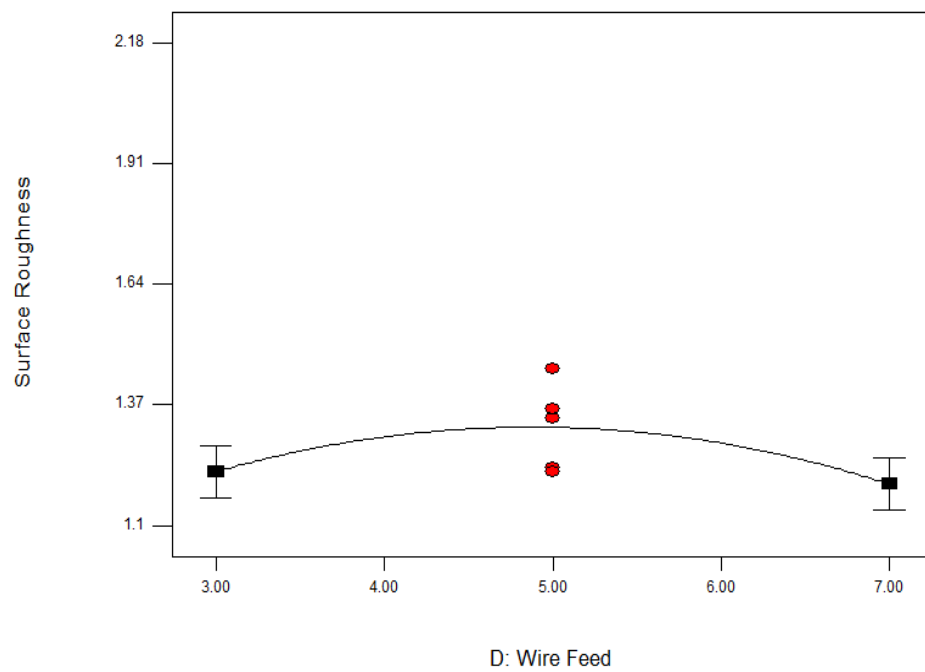


Figure 5.38 Effect of wire feed on surface roughness

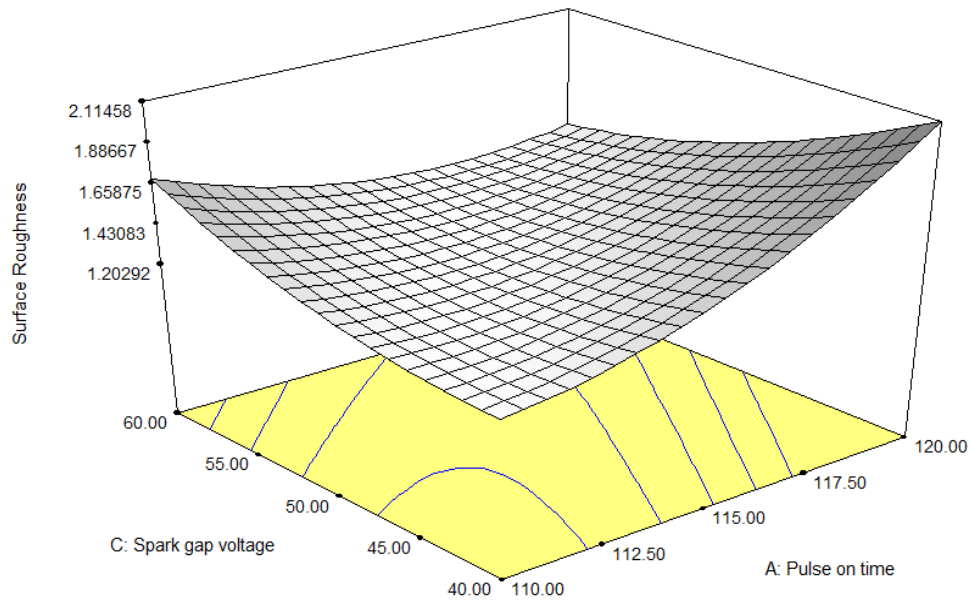


Figure 5.39 Interaction plot between spark gap voltage and pulse on time for surface roughness

5.3.2.3 Effect of process parameters on dimensional deviation

The impacts of process parameters got from ANOVA i.e. Ton, Toff, SV and WF for dimensional deviation are displayed in this section. The distinctive plots and collaboration diagram for dimensional deviation are demonstrated as follows:

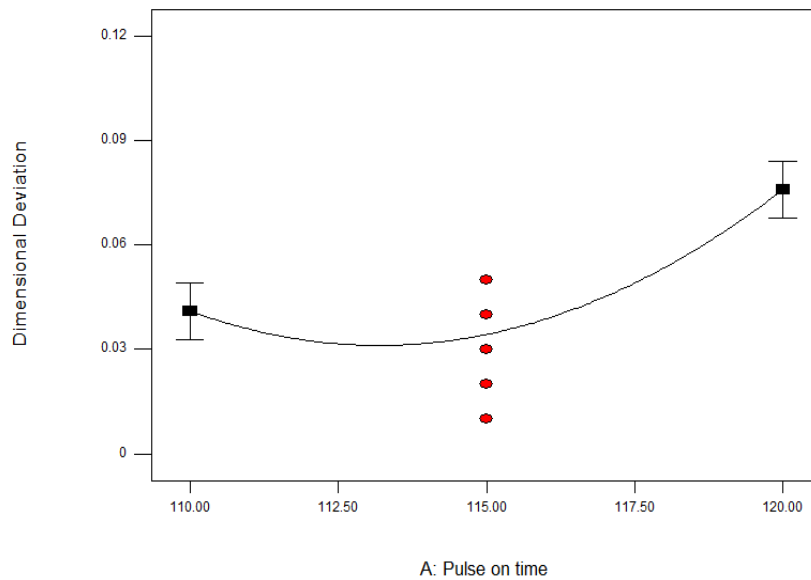


Figure 5.40 Effect of pulse on time on dimensional deviation

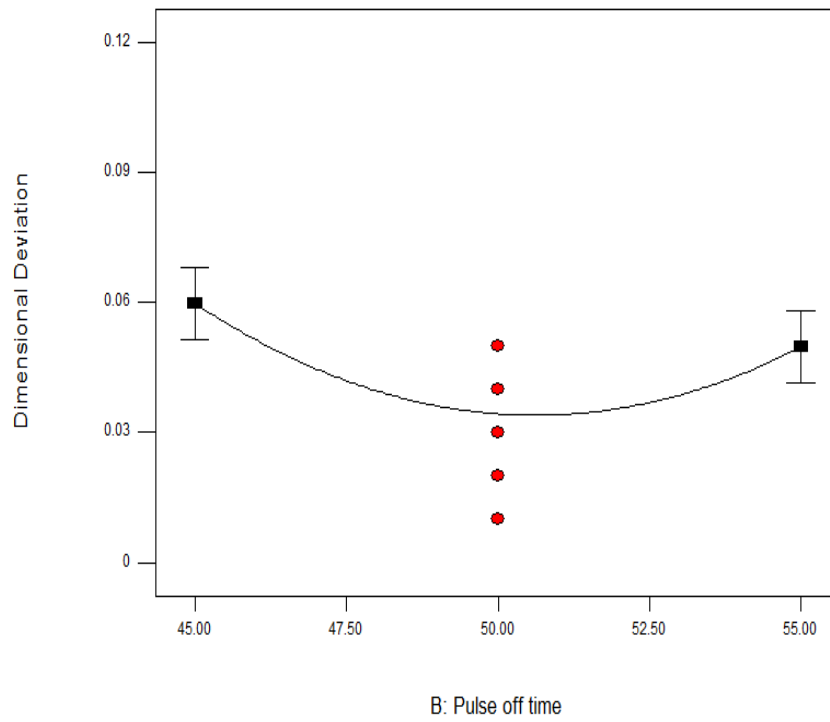


Figure 5.41 Effect of pulse off time on dimensional deviation

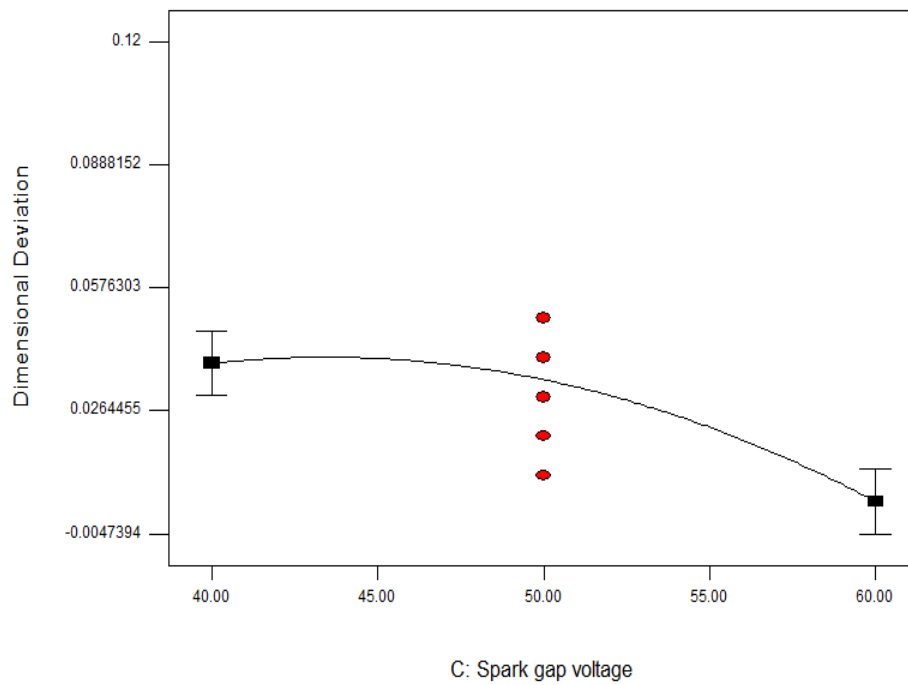


Figure 5.42 Effect of spark gap voltage on dimensional deviation

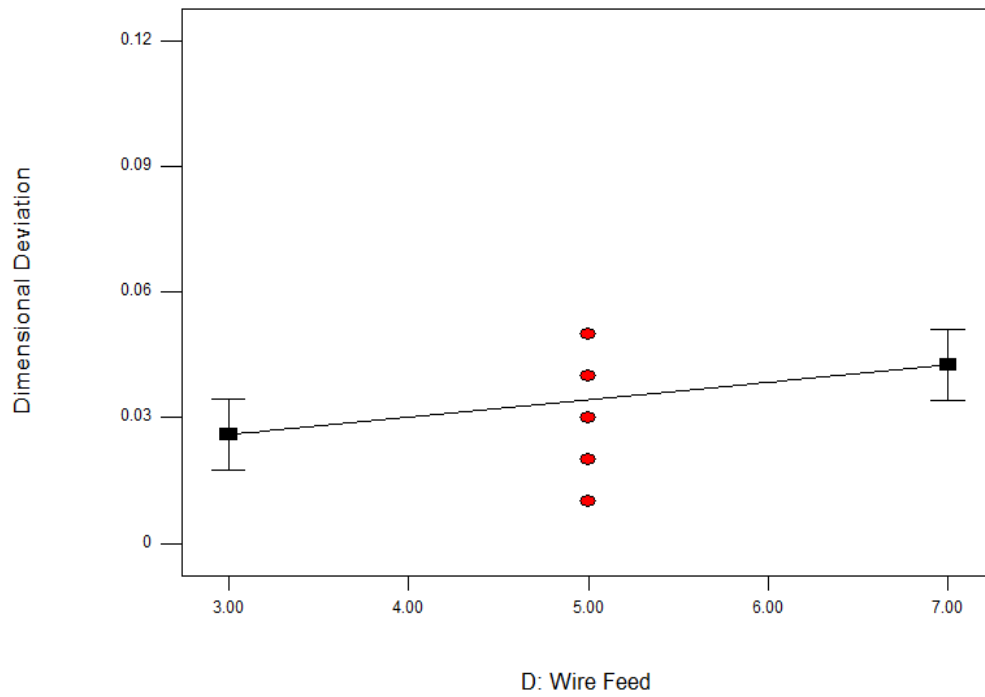
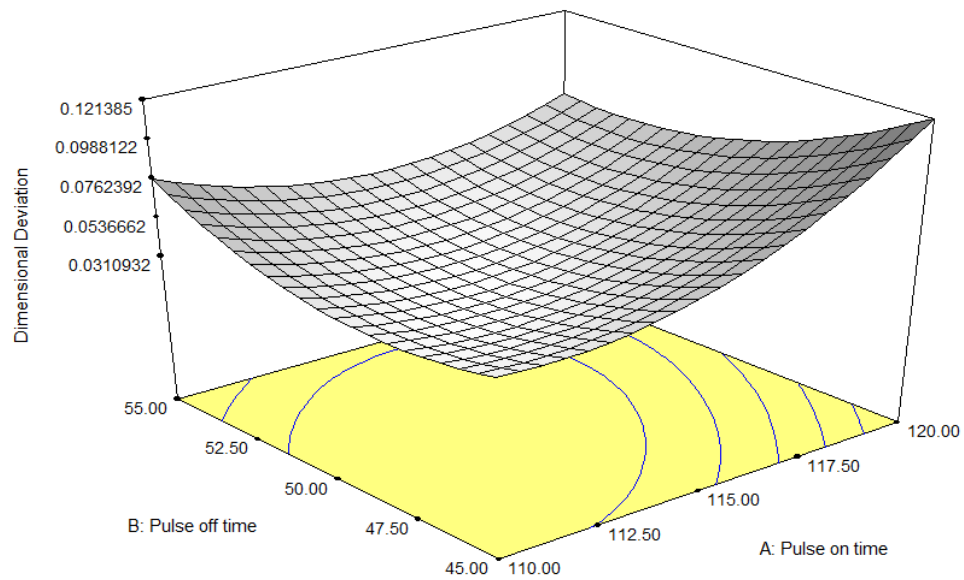
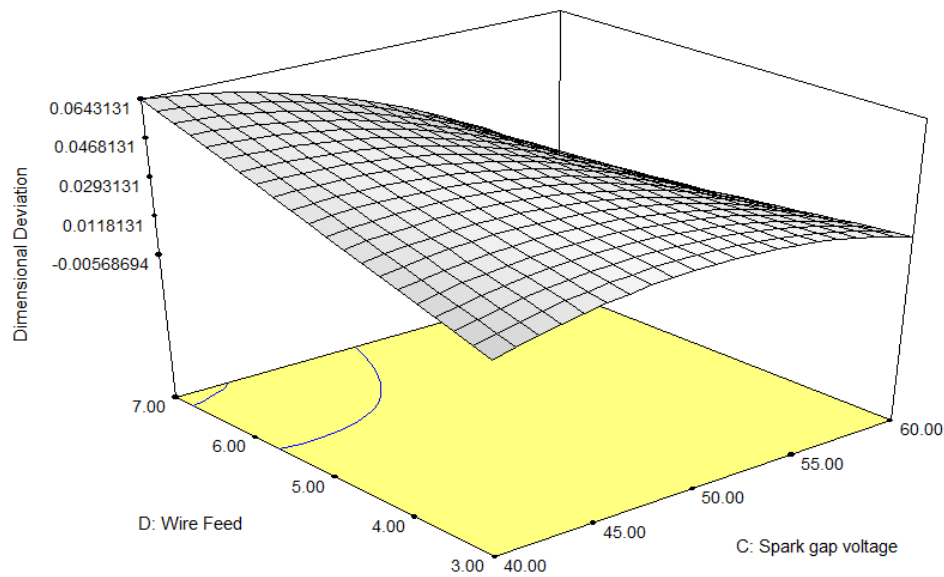


Figure 5.43 Effect of wire feed on dimensional deviation



(a)



(b)

Figure 5.44 Three dimensional interaction plots showing the effects of two parameters on dimensional deviation (a) pulse on time and pulse off time, (b) wire feed and spark gap voltage

5.4 MULTI-RESPONSE OPTIMIZATION USING DESIRABILITY FUNCTION

Multi-response optimization is a process of maintaining a balance between two or more than two responses. From productivity, surface quality and cost/ power consumption point of view, we often encounter response characteristics which are conflicting in nature. E.g. when cutting speed increases, surface finish decreases and gap current increases. Therefore, there is hardly any possibility of having a single optimal setting for all three responses. However, it is possible to consider the multi-response optimization problem into a single response problem by measurement of mathematical transformations.

Deringer and Suich (1980) presented a multi-response technique called desirability. It is very useful for optimization of multiple quality characteristics problem encountered during research work and for industry. This method is credited to be intuitive and simple and hence used widely. The inputs are mean response estimates, target value and upper and lower acceptability bounds. The individual desirability is combined using the geometric mean. The desirability of a product characteristics value depends on the lower

and upper ranges of product specification. Improper selection of ranges may result in a very different “optimum”.

The method followed in this work for concurrent optimization of the three responses is a amendment of the method developed by [Montgomery, 2002].

Step-1 Calculate the particular desirability (d_i) for every response ($\hat{y}$).

Step-2 Combining particular desirabilities to attain composite desirability (DG) for specified weights of cutting speed, surface roughness and dimensional deviation. Composite desirability is the weighted geometric mean of particular desirability for the specified responses.

Step-3 Enlarging the composite desirability and determining the best parameter combinations.

$$d_i = \begin{cases} 0 & \hat{y} < A_i \\ (\hat{y} - A_i / t_i - A_i)^w & A_i \leq \hat{y} \leq t_i \\ 1 & \hat{y} > t_i \end{cases} \quad (5.7)$$

If the target (t_i) is to reduce a response, the particular desirability (d_i) is calculated as

$$d_i = \begin{cases} 1 & \hat{y} < t_i \\ (B_i - \hat{y} / B_i - t_i)^w & t_i \leq \hat{y} \leq B_i \\ 0 & \hat{y} > B_i \end{cases} \quad (5.8)$$

Where,

A_i = lower limit value of response $\hat{y}$

B_i = upper limit value of response $\hat{y}$

If the object for the response is a goal value, then particular desirability (d_i) is calculated as:

$$d_i = [(\hat{y} - A_i) / (t_i - A_i)]^w \quad L_i \leq \hat{y} \leq t_i$$

$$d_i = [(B_i - \hat{y}) / (B_i - t_i)]^w \quad t_i \leq \hat{y} \leq B_i$$

$$d_i = 0 \quad \text{if } \hat{y} < A_i$$

$$d_i = 0 \quad \text{if } \hat{y} > B_i$$

If the significance is similar for each response, the composite desirability (DG) the geometric mean of every desirability functions and is given by

$$\text{Desirability Function (DG)} = (d_1 \times d_2 \times d_3 \times \dots \times d_n)^{1/n} = \left(\prod_{i=1}^n d_i \right)^{1/n} \quad (5.9)$$

Where n = no. of responses=3

It can be widespread to reflect the probable dissimilarity in the significance of different responses by giving weights. Where the weight w_i satisfy $0 < w_i < 1$ and $w_1 + w_2 + \dots + w_n = 1$

$$DG = (d_1^{w_1} \times d_2^{w_2} \times \dots \times d_n^{w_n})^{1/n} \quad (5.10)$$

The factor settings with highest total desirability are measured to be optimal parameter grouping. In the current work, desirability function is utilized to conclude the ideal parameter combinations for enhancement of cutting speed, surface roughness and dimensional deviation.

Table 5.17 shows the imperatives for carrying out optimization of responses i.e. cutting speed, surface roughness and dimensional deviation individually. Objectives to expand, minimize or to keep the response at an objective value and breaking points for control variables are set up for every response exclusively with a specific end goal to precisely decide their effect on individual desirability. Weights are appointed to give added accentuation to upper/lower limits or to emphasize a goal value. The default value '1' of weight is appointed to an objective to conform the state of its specific desirability function. The default value '3' and '5' taken by design expert® software is utilized to assign significance of target capacity.

Table 5.13 Constraints of input parameters and responses

Parameters	Target	Lower limit	Upper limit	Lower weight	Upper weight	Importance
T_{on}	In range	110	120	1	1	3
T_{off}	In range	45	55	1	1	3
SV	In range	40	60	1	1	3
WF	In range	3	7	1	1	3
Cutting speed	maximize	0.24	1.04	1	1	5
Surface roughness	minimum	1.15	2.97	1	1	3
Dimensional deviation	minimum	0	0.12	1	1	3

Table 5.14 Optimal solutions for cutting speed, surface roughness and dimensional deviation for non-cryogenated samples

Number	Pulse on time (mu)	Pulse off time (mu)	Spark gap voltage (V)	Wire Feed (m/min)	Cutting Speed (mm/min)	Surface Roughness (μm)	Dimensional Deviation(mm)	Desirability
1	115.37	45.02	40	3	0.964	1.788	0.0374	0.767
2	115.35	45.06	40	3	0.960	1.783	0.0370	0.767
3	115.47	45.32	40	3	0.953	1.799	0.0345	0.767
4	115.4	45.07	40	3.01	0.963	1.791	0.0370	0.767
5	115.11	45.03	40	3	0.945	1.735	0.0376	0.767
6	115.4	45.12	40	3.03	0.961	1.792	0.0369	0.766
7	116.04	45.43	40	3	0.988	1.915	0.0334	0.765
8	115.28	45.6	40	3.05	0.924	1.755	0.0330	0.764
9	115.38	45	40	3.12	0.966	1.791	0.0394	0.763
10	115.63	46.46	40	3.01	0.90	1.801	0.0253	0.762
11	115.86	45	41.03	3	0.975	1.825	0.0400	0.759
12	114.3	45.01	40	3.24	0.892	1.589	0.0418	0.752
13	115.46	45.79	40	3.46	0.924	1.785	0.0375	0.748
14	115.11	45	40	3.54	0.945	1.736	0.0451	0.747
15	117.99	47.66	45	3	0.885	1.908	0.0272	0.73
16	113.69	45	40	4.45	0.853	1.488	0.0518	0.718
17	119.11	50.04	46.05	3	0.825	1.927	0.0174	0.714
18	119.36	49.28	47.72	3	0.839	1.916	0.0233	0.712
19	110.87	45	40	7	0.716	1.154	0.0380	0.712
20	111.11	45	40	6.89	0.726	1.174	0.0406	0.71
21	111.41	45	40	6.88	0.739	1.202	0.0432	0.709
22	112.55	45	40	5.59	0.791	1.329	0.0524	0.702
23	112.75	45	40	5.58	0.801	1.353	0.0535	0.702
24	112.23	45	40	5.87	0.775	1.289	0.0509	0.701

This information is utilized for completing multi-target optimization of cutting speed, surface roughness and dimensional deviation utilizing design expert® are introduced as a part of Table 5.14 and Table 5.15. The solution which has desirability more closer to one is chosen as the ideal parameter combination.

Figure 5.45 to 5.50 demonstrates the three dimensional response surface, streamlined bar histograms and slope charts for general desirability of the considerable number of responses i.e. cutting speed, surface roughness and dimensional deviation.

Table 5.15 Optimal solutions for cutting speed, surface roughness and dimensional deviation for cryogenated samples

Number	Pulse on time (mu)	Pulse off time (mu)	Spark gap voltage(V)	Wire Feed (m/min)	Cutting Speed (mm/min)	Surface Roughness (μm)	Dimensional Deviation (mm)	Desirability
1	115.12	45	40	3	1.050	1.398	0.0378	0.786
2	115.32	45.01	40	3	1.062	1.422	0.0376	0.785
3	115.07	45.01	40	3.01	1.046	1.393	0.0380	0.785
4	115.3	45.18	40	3	1.050	1.422	0.0359	0.784
5	114.76	45	40.1	3	1.023	1.352	0.0387	0.783
6	115.79	45	40	3	1.094	1.482	0.0374	0.782
7	114.81	45	40.31	3	1.022	1.353	0.0391	0.781
8	115.26	45	40	3.08	1.059	1.424	0.0389	0.78
9	114.99	45	40	3.17	1.041	1.399	0.0401	0.775
10	114.9	45	40	3.33	1.035	1.404	0.0423	0.766
11	115.92	48.01	40	3	0.928	1.502	0.0151	0.748
12	116.24	45.08	43.61	3	1.026	1.432	0.0447	0.747
13	112.26	45.01	40	6.84	0.871	1.098	0.0515	0.726
14	112.3	45	40	6.91	0.875	1.093	0.0521	0.726
15	112.16	45.08	40	6.78	0.862	1.1	0.0500	0.725
16	111.9	45.12	40	7	0.845	1.055	0.0469	0.724
17	111.87	45	40	6.53	0.850	1.1	0.0480	0.723
18	111.79	45	40	6.46	0.845	1.099	0.0474	0.722
19	112.18	45	40	6.15	0.867	1.155	0.0506	0.716
20	112.33	45.07	41.04	6.79	0.850	1.099	0.0509	0.715
21	112.36	45	40	5.56	0.878	1.203	0.0514	0.71
22	112.66	45	40	5.27	0.896	1.237	0.0522	0.71
23	115.68	50.21	40	3.04	0.806	1.449	0.0096	0.705
24	118.62	48.32	48.06	3	0.882	1.538	0.0270	0.69
25	112.25	45	53.18	7	0.582	1.123	0.0175	0.598

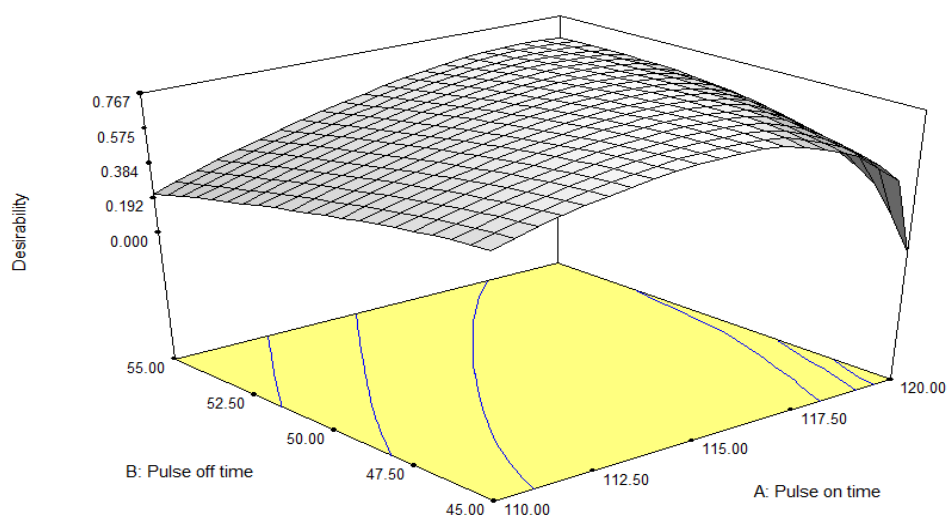


Figure 5.45 3D surface plot of composite desirability for all responses of untreated samples

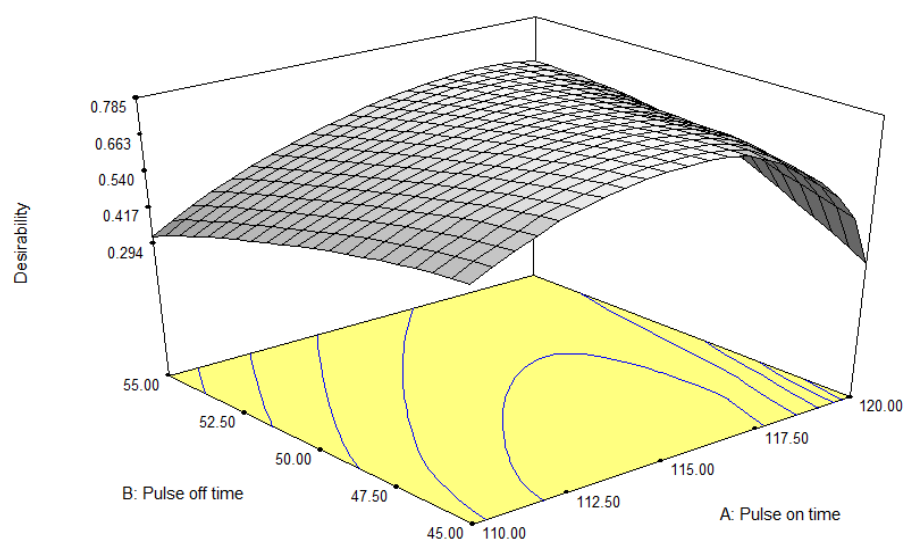


Figure 5.46 3D surface plot of composite desirability for all responses of cryogenated treated samples

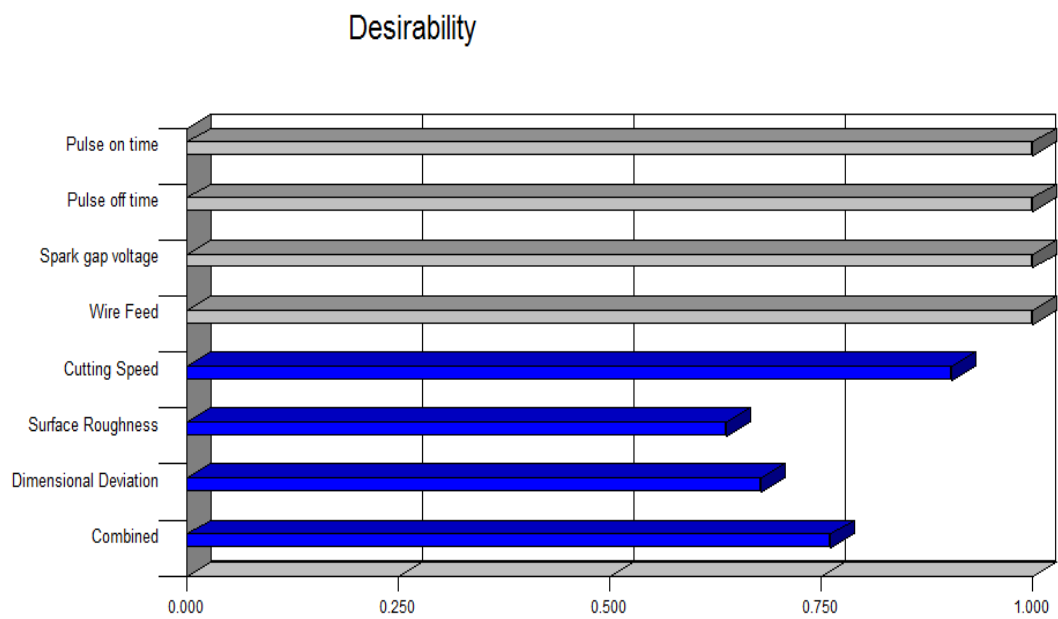


Figure 5.47 Bar histogram plot of composite desirability for all responses of untreated samples

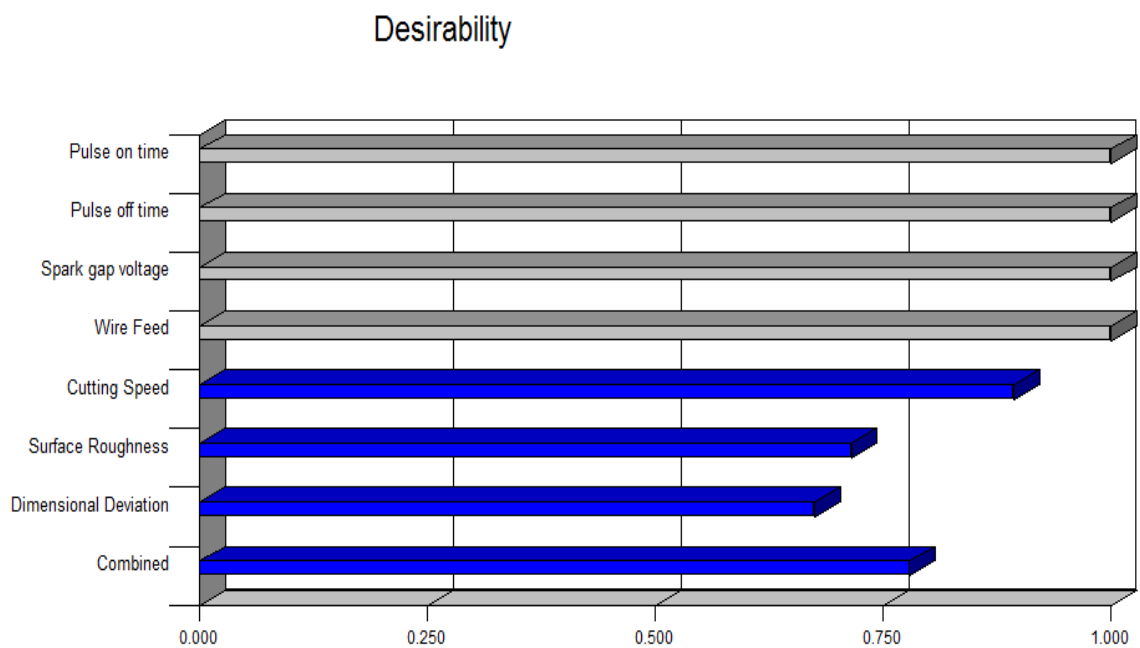


Figure 5.48 Bar histogram plot of composite desirability for all responses of cryogenated treated samples

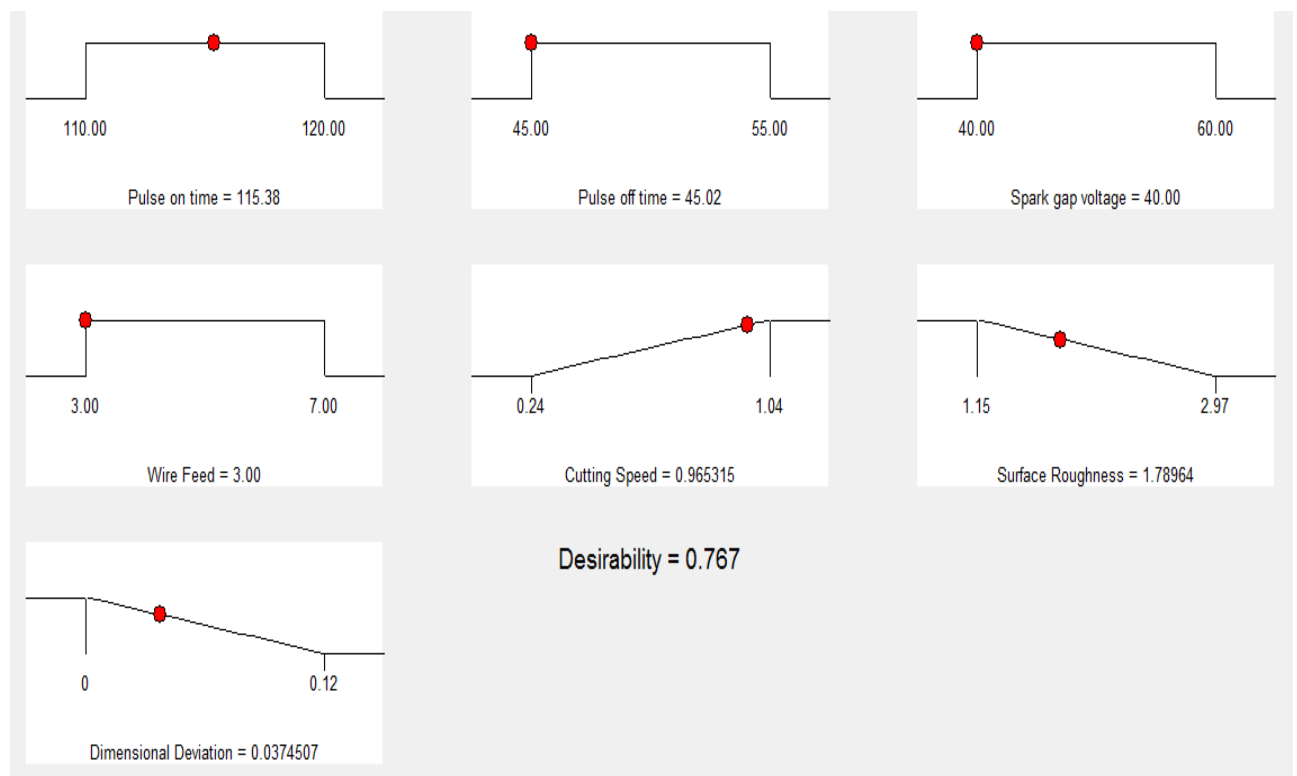


Figure 5.49 Ramp graph of optimal setting for all responses of untreated samples

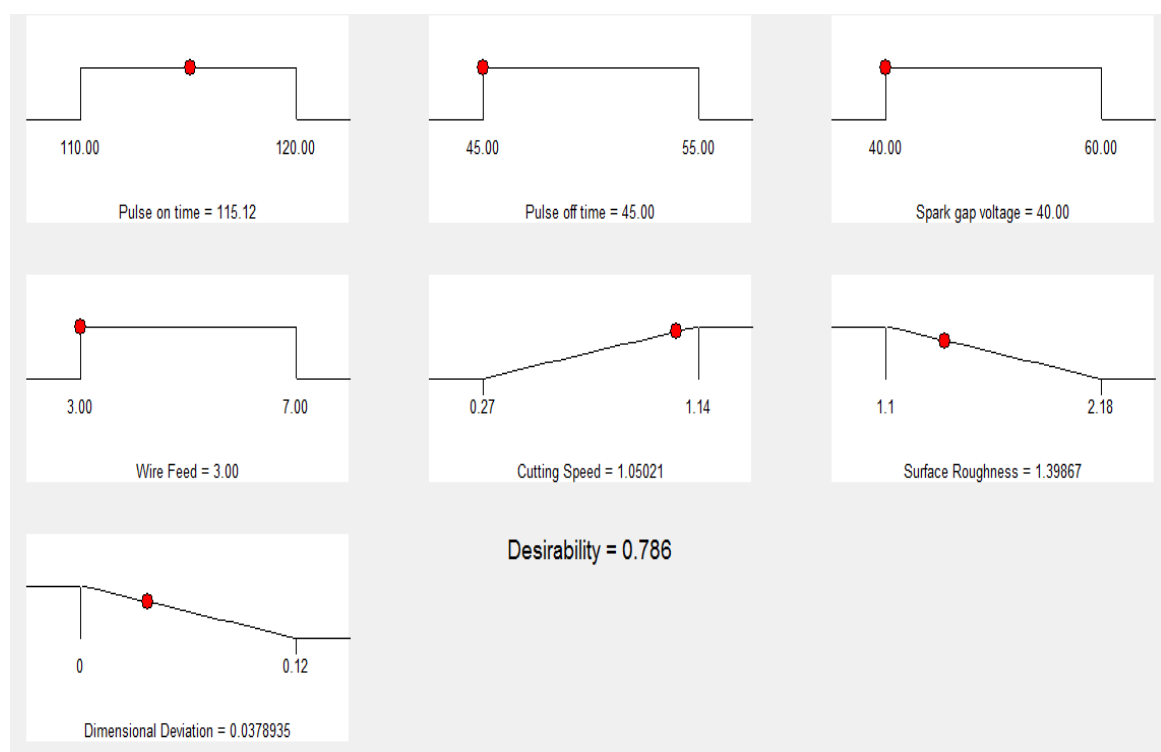


Fig: 5.50 Ramp graph for optimal setting of all responses of cryogenated treated samples

5.5 MICROSTRUCTURE CHARACTERISTICS AND MATERIAL TRANSFORMATION ANALYSIS OF MACHINED SURFACES

The present research work is mostly focused on the inspection of integrity of the work surface and wire electrode surface after machining with WEDM. Experimental results demonstrated that pulse on time and pulse off time considerably affected the surface integrity with the growth of deep-wide overlapping craters, debris, micro cracks and recast layer. The discharge energy encroached on the work piece during WEDM melts the material and debris are flushed away by dielectric. Thermal action of EDM process affect the surface integrity of a machined part [Yadav et al., 2002]. Thus the surface integrity analysis is done with a view to inspect the parametric influence on the surface defects i.e. cracks, voids roughness as well as additionally on the thickness of the recast layer deposited on the machined surface. Much work has been devoted to the study of surface integrity in WEDM of regular steel alloys, particularly tool and die-steels. However, little research has been found on the effects of WEDM on the surface characteristics of M42 HSS. Specifically, no significant literature has been found relating to surface integrity of M42 HSS.

The following subsections investigate the effect of process parameters on microstructure and the thickness of recast layer produced in the machined M42 HSS samples.

5.5.1 Material and test condition

During the experimentation work, parameters such as pulse on time, pulse off time, spark gap voltage and wire feed were varied to explore their effects on surface integrity of M42 HSS. After WEDM, the metallographic investigations of the machined samples were made using scanning electron microscope (SEM). In present study, the surface integrity was analyzed by using the scanning electron microscope(SEM). The samples were cleaned with acetone ($\text{CH}_3)_2\text{CO}$.

5.5.2 Results and discussion on machined surface topography and micro-cracks creation

The nature of a machined surface is for the most part described by surface geography which incorporates miniaturized scale breaks, heat influenced zone, recast layer and stage changes at first glance and subsurface locales. The surface properties may be changed because of impact of procedure parameters, for example, pulse on time, pulse off time, spark gap voltage and wire feed. It was seen from SEM micrographs, that machined

surface contained globules of debris, spherical particles, craters and micro-cracks. The increase in pulse on time brought about the development of profound craters on the machined surface. These profound and covering pits were shaped because of successive electrical discharges, extreme heat exchanged to the surface of the specimen which brought about confined dissolving or evaporization of work material. A portion of the molten material delivered by the discharge was carried away by the deionized water.

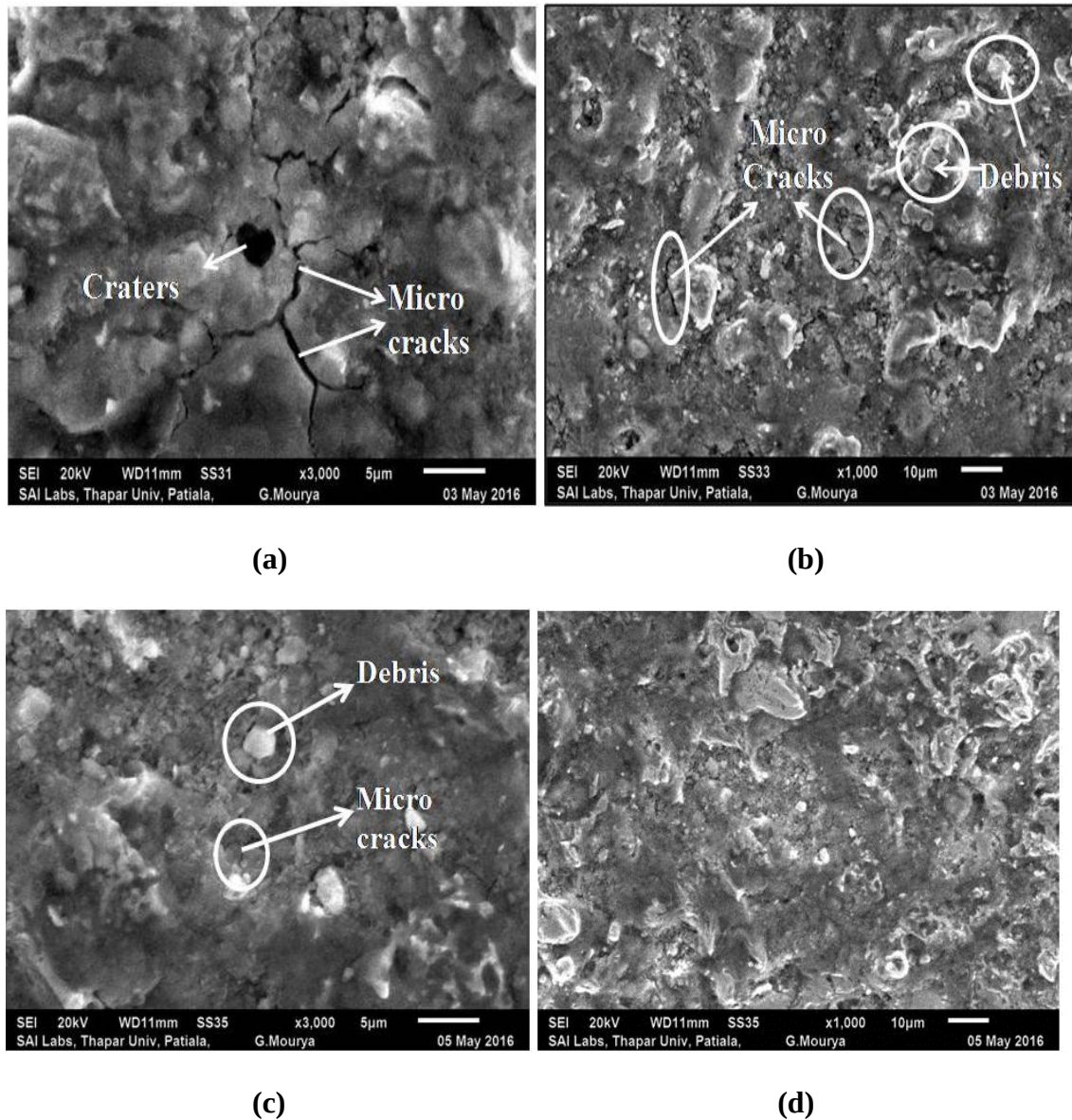


Figure 5.51 SEM micrographs of untreated sample(a,b) and cryogenated treated samples(c,d) observed with Cracks, Craters and Debris at higher pulse on time = 120 μ s, pulse off time = 45 μ s, Spark gap voltage= 50 V and R_a = 2.36 μ m. (Source: Sai Labs, Thapar University, Patiala)

The fundamental conceivable explanation behind deep and huge craters is the oxidation reaction, the incautious force of dielectric pressure focused on confined spark hole area. Because of low peak current and pulse on time, the work surface is encroached with less intensive discharge. High peak current and low pulse off time expanded the debris in the spark gap, which lead to irregular arcing. The anomalous arcing diminishes the discharge rate and material expulsion rate [Sarkar et al.; 2010].

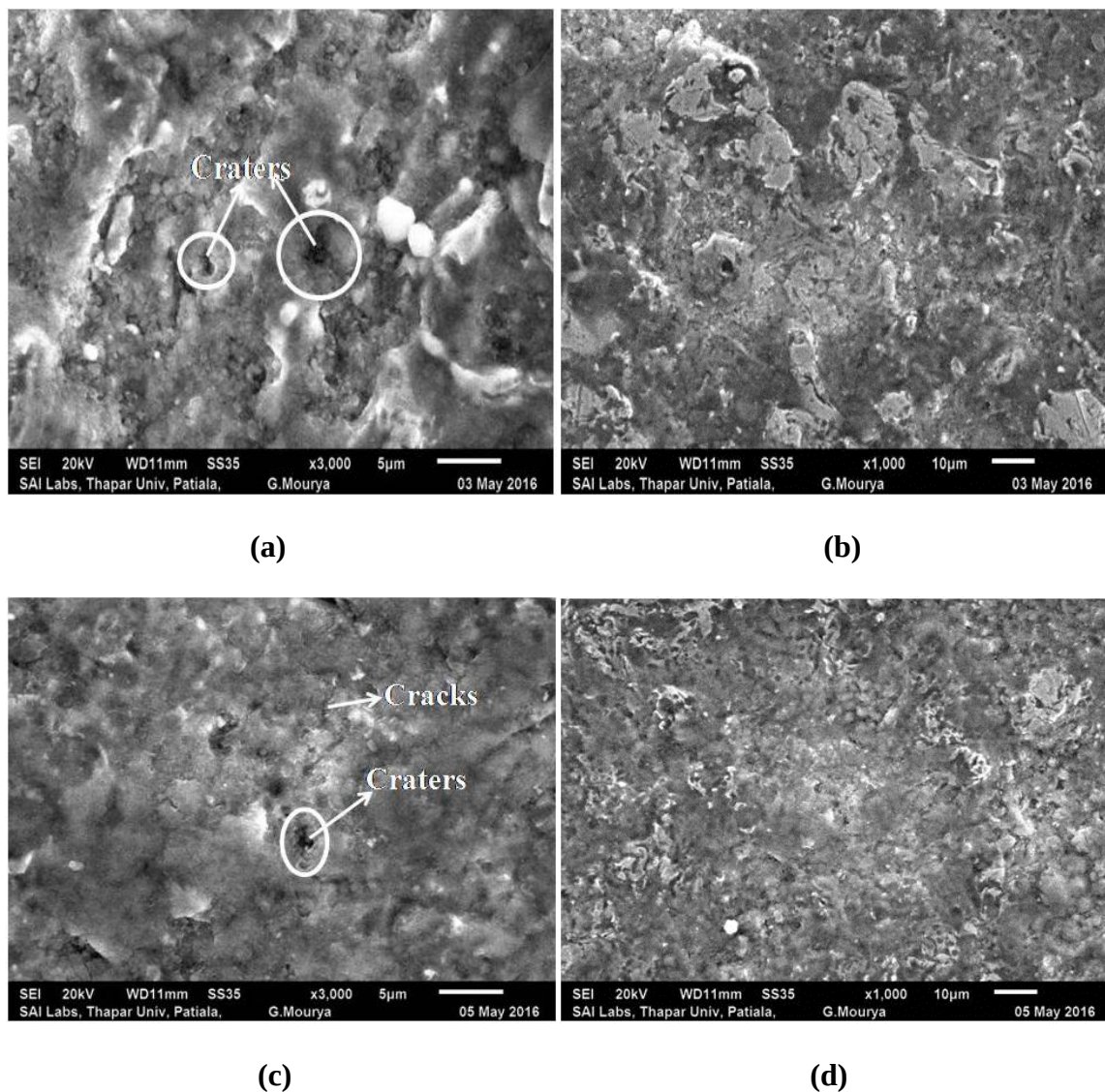


Figure 5.52 SEM micrographs of untreated sample(a,b) and cryogenated treated samples(c,d) observed with Cracks, Craters and Debris at higher pulse on time = 120 μ s, pulse off time = 50 μ s, Spark gap voltage= 60 V and Wire feed= 5 m/min

Here the SEM images of the M42 HSS samples which are machined with untreated and cryogenated treated EDM brass wire is shown below. The surface topography, debris formation and micro-cracks formation is compared between untreated and cryogenated treated samples. The SEM images are obtained at different setting of process parameters to check the effect on surface roughness in both cases.

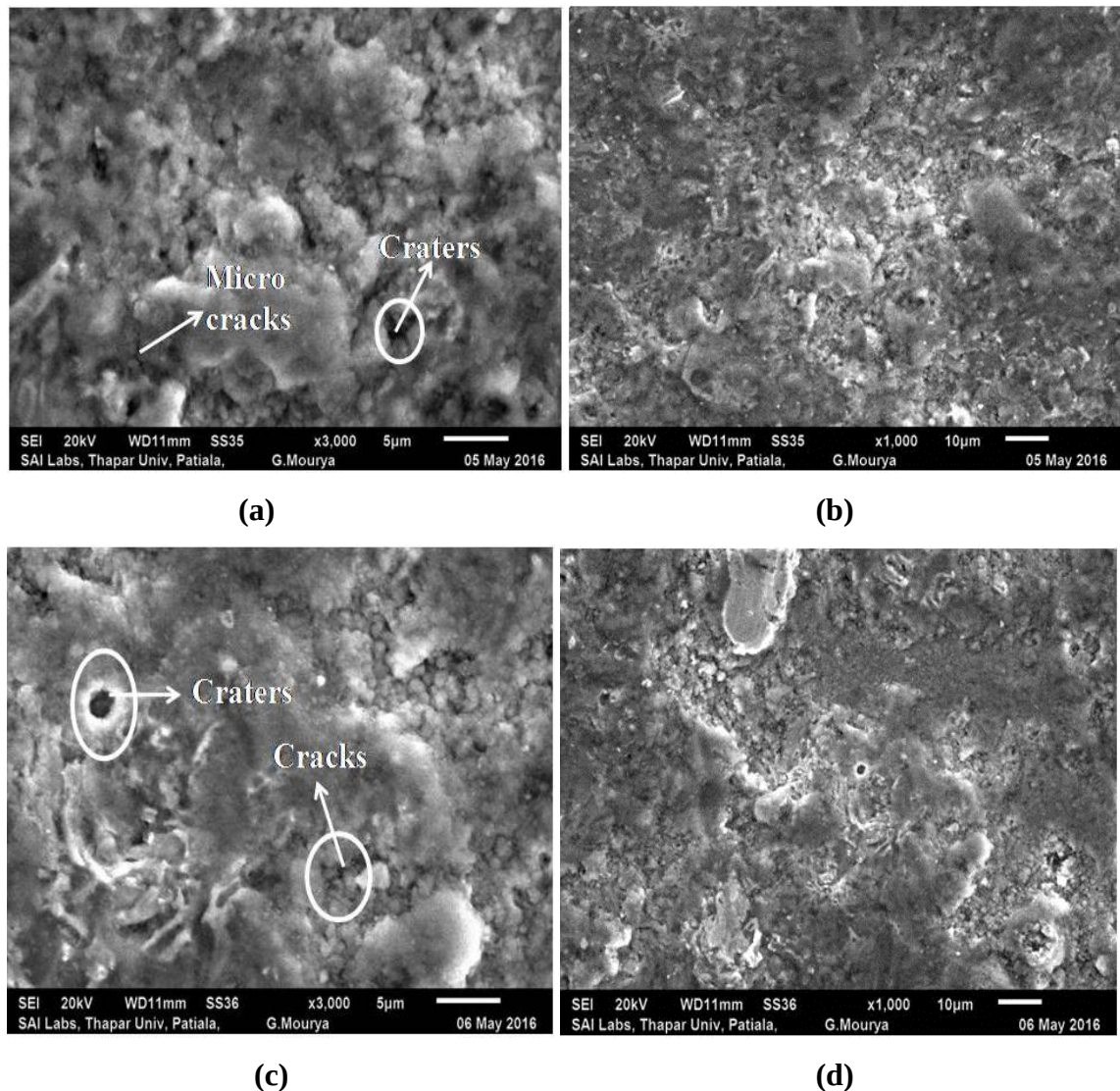


Figure 5.53 SEM micrographs of untreated sample(a,b) and cryogenated treated samples(c,d) observed with Cracks, Craters and Debris at lower pulse on time = 110 μ s, pulse off time = 50 μ s, Spark gap voltage= 60 V and Wire feed= 5 m/min

5.5.3 Results and discussion the on recast layer (RL)

Recast layer was observed at the cross section of the WEDM surface. The recast layer(RL) is defined as the material melted by electrical discharge and re-solidified on the

work surface without being ejected nor removed by dielectric fluid [Lee, 2003]. It is very difficult to remove and its appearance is observed through a scanning electron microscope at diverse levels of magnification. Below the recast layer there is the heat-affected zone(HAZ).

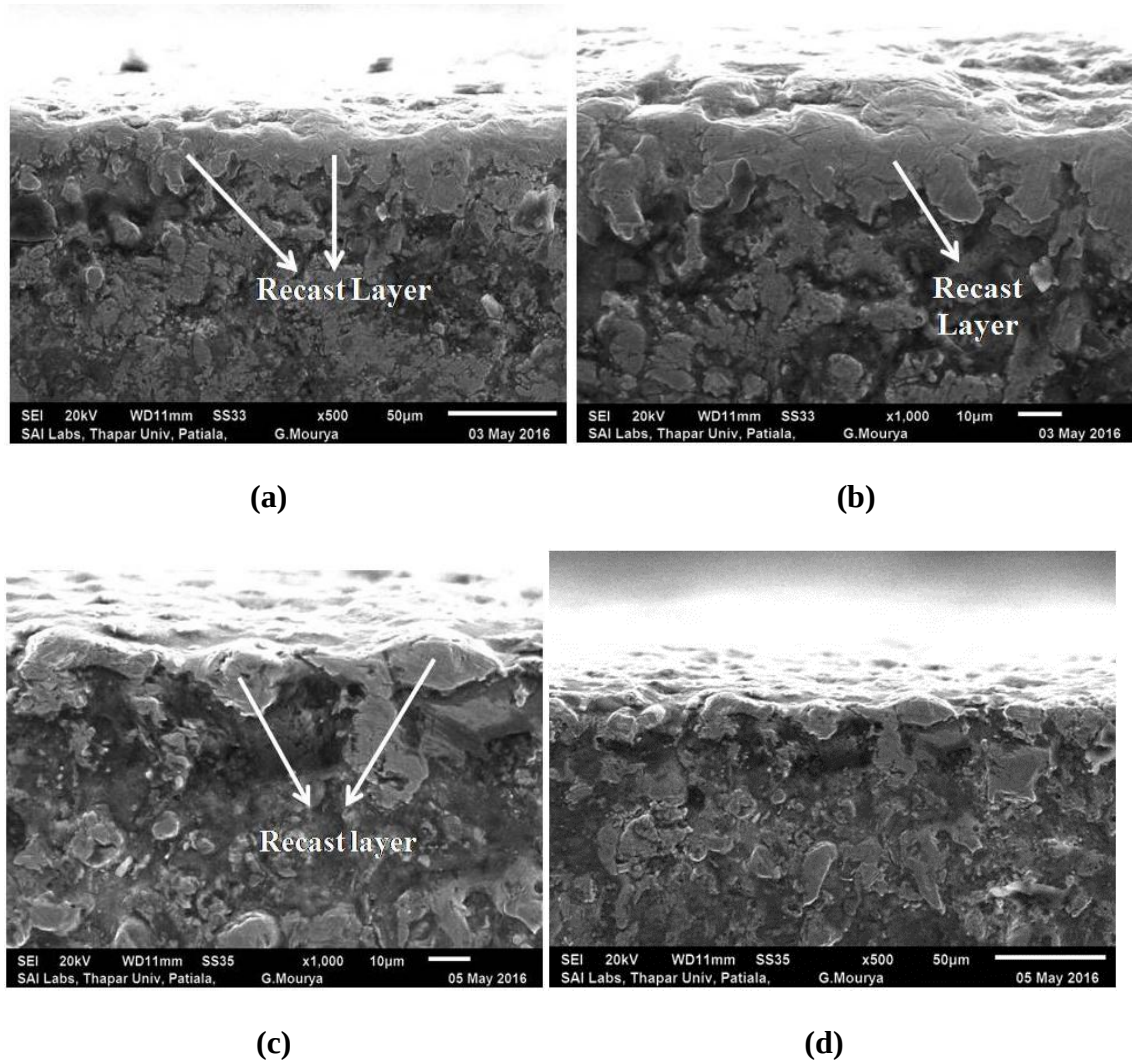


Figure 5.54 SEM micrographs of recast layer and heat affected zone (HAZ) for untreated samples(a,b) and cryogenated treated samples(c,d) at higher pulse on time = 120μs, pulse off time = 45μs, spark gap voltage = 50V and wire feed=5 m/min

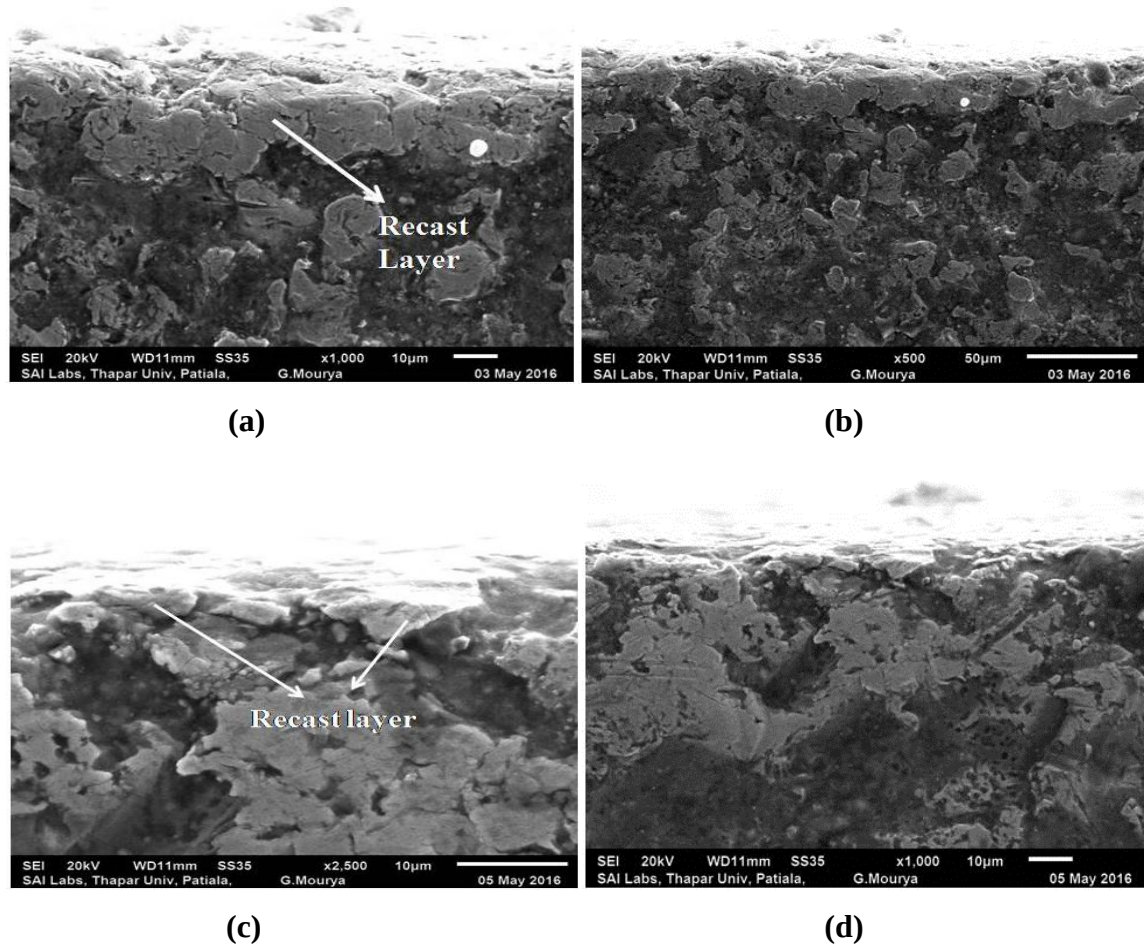


Figure 5.55 SEM micrographs of recast layer and heat affected zone (HAZ) for untreated samples(a,b) and cryogenated treated samples(c,d) at higher pulse on time = 120μs, pulse off time = 50μs, spark gap voltage = 60V and wire feed=5 m/min

The recast layer thickness was changed because of evident solidifying of the work material by the discharge heat of electrical spark. The power of spark depend on peak current, pulse on time and pulse off time. The thickness of recast layer of WEDM surface was expanded because of raise of pulse on time and reduction of pulse off time. Because of increase of pulse on time the melting of isothermals turns out to be more severe, which further enters into base metal and result in the increase in the thickness of recast layer. It is clear that recast layers show up as non-uniform and have wave like pattern. The micro cracks cleaving in the matrix have harmfull effect on mechanical properties . The service life of materials with small scale splits will be diminished to a great degree, particularly in weariness and erosion environment. The micro-cracks occuring in the recast layer were seen because of the heat of corrosive debris and shaped in a thick, coarse dendrite structure [Rajesha et al., 2012].

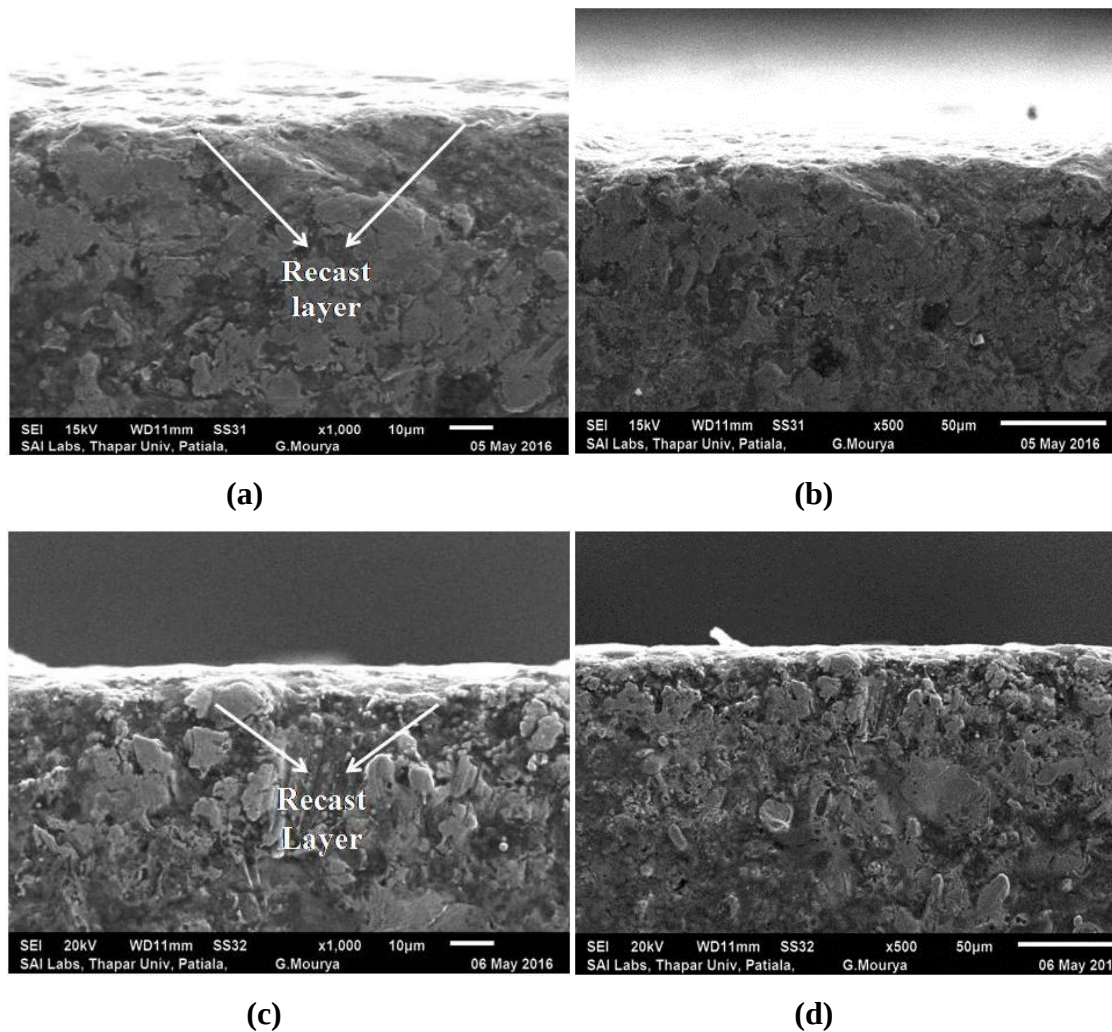
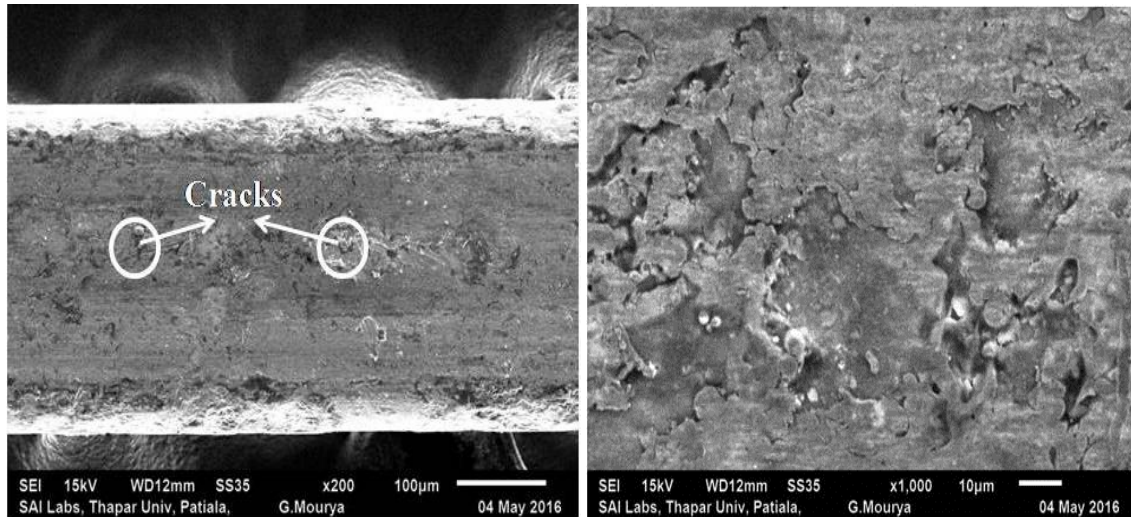


Figure 5.56 SEM micrographs of recast layer and heat affected zone (HAZ) for untreated samples(a,b) and cryogenated treated samples(c,d) at lower pulse on time = 110µs, pulse off time = 50µs, spark gap voltage = 60V and wire feed=5 m/min

It is clearly observing from the SEM images that at high pulse on time there is more thick formation of recast layer in both untreated and cryogenated treated samples and with more pulse off time and less pulse on time, there is less formation of recast layer. In cryogenated samples there are less cracks and debris because of the improved properties of the brass wire with the help of cryogenic treatment.

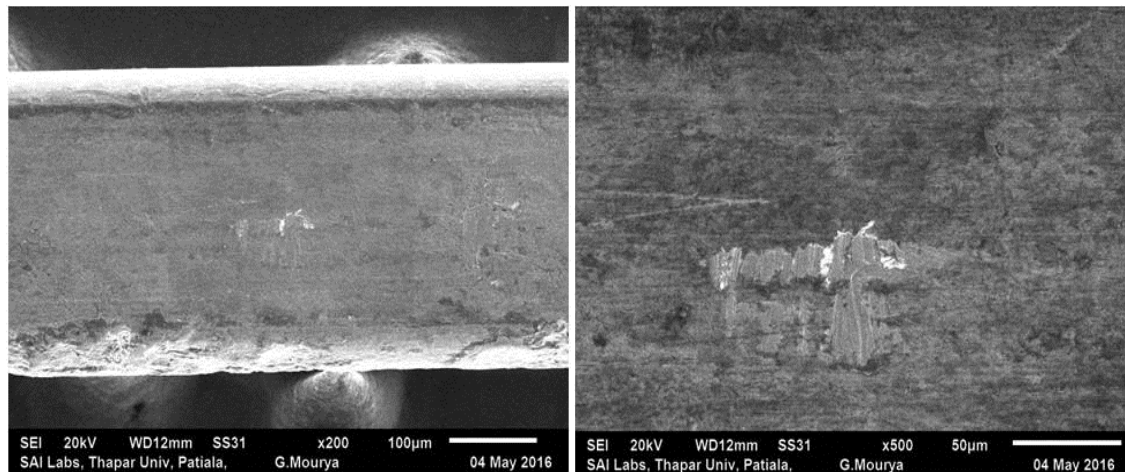
5.5.4 Analysis of the wire electrode surface topography

The thermal stresses developed at the boundary zone among the tool and work resulted in microstructure changes [Tosun et al., 2003]. Therefore, the material move characteristics of wire were researched.



(a)

(b)



(c)

(d)

Figure 5.57 SEM view of non-cryogenated(a,b) and cryogenated wire(c,d) after WEDM of M42 HSS using deionized water at pulse on time 120 μ s, pulse off time 45 μ s, spark gap voltage 50 v and wire feed 5 m/min

In present study, two sorts of wire one is non-cryogenated and other is cryogenated treated, surface characteristics were observed. The diverse craters and residuals of debris held to the surface of wire electrode. This may be owing to the melting and re-solidification of M42 HSS and brass wire electrode after WEDM. The increase of peak current leads to generation of higher discharge energy in the spark gap. Hence it may possibly result in increase of wear of wire electrode.

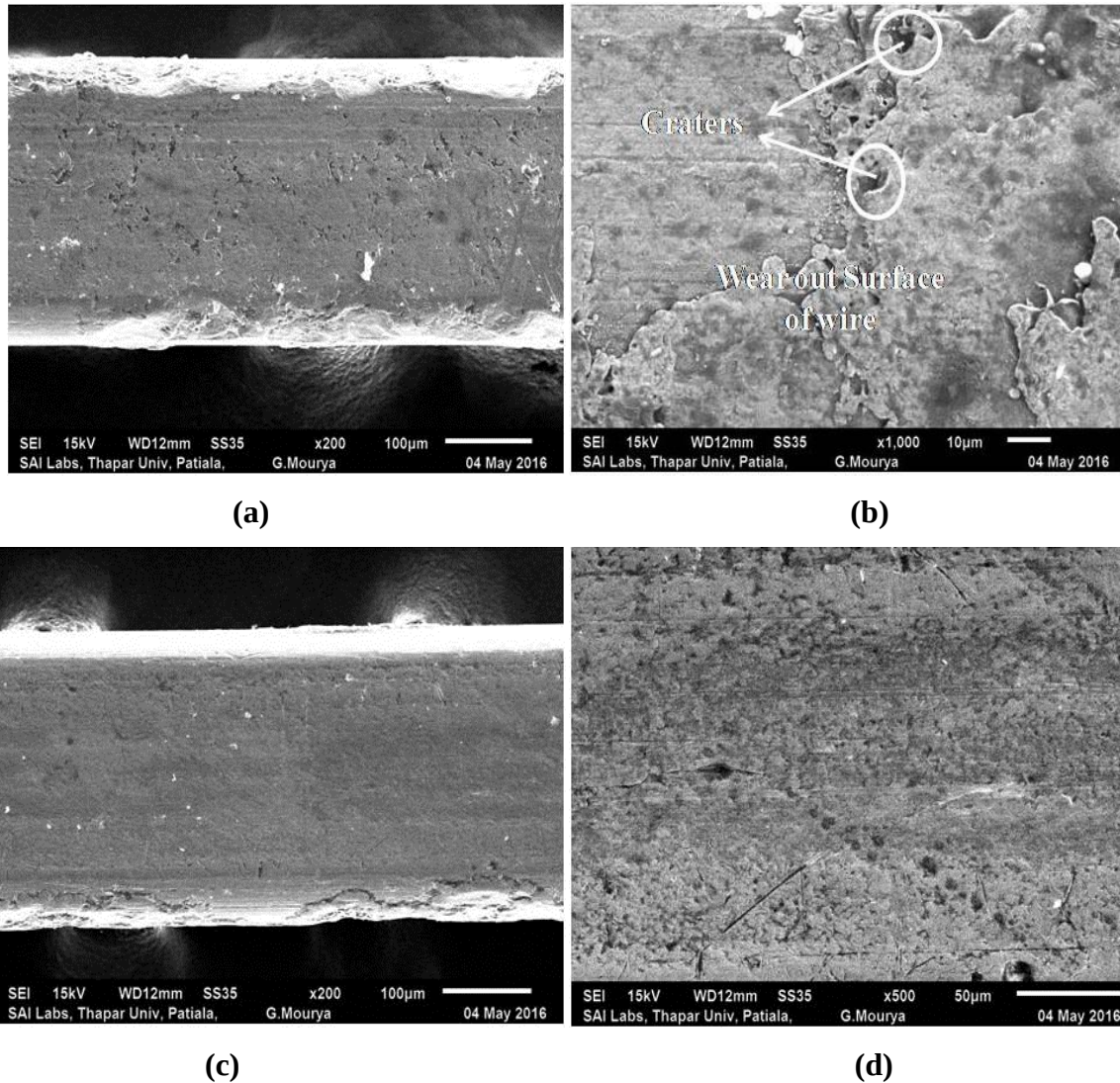


Figure 5.58 SEM micrographs of the machined wire electrode surface for untreated(a,b) and cryogenated(c,d) at pulse on time 120 μ s, pulse off time 50 μ s, spark gap voltage 60 V and wire feed 5 m/min

From the above SEM micrographs for the wire electrode surface it is concluded that the wear out surface in case of untreated wire is more than the cryogenated treated wire because in case of cryogenated, the wire properties get improved by giving it cold treatment at -110°C (shallow cryogenic treatment). The wear out surface, debris and crack formation is less after machining on WEDM on cryogenated wire.

CONCLUSIONS AND SCOPE FOR FUTURE WORK

The investigations into WEDM process for exploring the possibility of improvement in its process efficiency by using cryogenically treated wire electrodes have led to useful results. The important conclusions have been listed in Section 6.1. Section 6.3 present the scope for future work that may be helpful to the manufacturers of wire electrodes, the users and the researchers engaged in WEDM technology.

6.1 CONCLUSIONS

Following conclusions have been made in the present experimental and analytical work within the range of test conditions employed.

1. The use of shallow cryogenically treated wire electrode in WEDM for machining of M42 High Speed Steel(HSS) enhanced the cutting speed. Less time is required for processing of same amount of workpiece material. Superior surface finish of machined workpiece and less wire wear of wire is also obtained with cryogenically treated wire electrodes as compared with untreated wire electrode.
2. The effect of shallow cryogenic treatment on wire electrode in WEDM enhanced the cutting speed by 8%, significant improvement in surface roughness value respectively.
3. Electrical conductivity of brass wire electrode is enhanced with shallow cryogenic treatment. Shallow cryogenic treatment improved the conductivity to 27.90 (%IACS) respectively, as compared to 22.50 (%IACS) of untreated brass wire electrode.
4. The SEM photographs of wire electrode surface treated by shallow cryogenic treatments suggest that the soundness of electrodes is higher than that of untreated wire electrode.
5. The SEM photographs of workpiece surfaces processed by shallow cryogenic treated wire electrode in WEDM suggest that surfaces are more uniform and smooth than produced with untreated wire electrode in WEDM.

6. Type of wire, pulse width, time between two pulses significantly affects (at 95% confidence interval) the Cutting Speed(CS) and Surface Roughness(Ra)
7. Pulse width and time between two pulses interact with type of wire while affecting the CS, Ra. This interaction signifies that low value of time between two pulses and shallow cryogenic treated wire electrodes is recommended combination for higher cutting speed. The low value of pulse width and Shallow cryogenic treated wire electrode is recommended setting for minimum Ra.
8. The material removal mechanism with shallow cryogenic treated wire electrode is proposed on the basis of the SEM examination of workpieces and wire electrodes, which is summarized as:
 - The spark gap distance is enhanced with more conductive cryogenic treated wire electrode as compared to untreated wire electrode.
 - The wider discharge gap might have caused due to more electron emission.
 - High conductive wires enable quicker propagation of heat along the surface.
 - Even discharge energy in the gap resulting from series discharge effect. As a result, shallow, uniform and flat craters are formed on the workpiece and wire electrode surface.
9. The experimental results indicate that the behavior of response characteristics (CS, Ra, DD) in WEDM depends upon the wire electrode (type of wire) and machine based parameters.
10. In the present research, the parametric optimization of process parameters with shallow cryogenic treated wire electrodes in WEDM indicates that the optimal settings of experimental results suggested by Box Behnken Design(BBD) lies well within the predicted range.
11. The multi-response optimization model developed based on “desirability concept” provides a simplified method for investigating the combined effect of any number of process parameters on the quality characteristics of the process. The predicted results agree with the experimental results within the specified range of parameters.

6.2 LIMITATIONS OF THE RESEARCH

1. The present research work is related with the machining of conductive material only. The machining of cryogenically treated wire on non-conductive electrodes has not been considered in the present study.
2. The study has been limited to the statistical analysis and modeling of selected
3. performance characteristics, like CS, Ra and DD only.
4. The wire electrodes other than brass wire have not been were not considered for the present study.
5. Thermal stress analysis in the workpiece has not been investigated in the present research work.

6.3 SCOPE FOR FUTURE WORK

Some of the issues, which can be examined in future research work are summarized as:

1. The possible use of cryogenic treated wire electrode for non conductive and composite materials (Ceramic, fiberglass etc.) could also be investigated.
2. The experimental study/theoretical analysis of surface modification/surface integrity of workpiece surfaces processed by cryogenic treated wire electrode in WEDM could be taken as future work.
3. The cryogenic treatment of composite and micro-wires for WEDM could be explored in future research work.
4. The thermal analysis of workpieces machined with cryogenically treated wire electrode for WEDM with finite element modeling technique could be used to predict temperature distribution. The theoretical estimated cutting speed (CS) values thus obtained could be compared with the experimental values.

6.4 CONCLUDING REMARKS

From the research work, it has been concluded that the shallow cryogenically treated wire electrodes have enhanced the cutting speed, improved the surface finish and wire wear is significantly found less. The soundness of wire electrode is improved owing to reduction in grain size with cryogenic treatment. The parametric optimization of process parameters with cryogenic treated and untreated wire electrode has been conducted, so that WEDM

process efficiency could be effectively enhanced in industrial setups. Few limitations of the study have been summarized. Some of the issues for future work have been proposed, so that these could be taken up by the researchers for further research work.

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APPENDIX I

Table A: Conversional table for pulse on Time from machine Units (mu) to micro seconds (μs)

T_{on} (mu)	T_{on} (μs)	T_{on} (mu)	T_{on} (μs)	T_{on} (mu)	T_{on} (μs)	T_{on} (mu)	T_{on} (μs)
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	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

Legend: TON- Pulse on time, mu- machine units, μs- micro seconds

Table B: Conversional table for pulse off time from machine units (mu) to micro seconds (μs)

T_{off} (mu)	T_{off} (μs)	T_{off} (mu)	T_{off} (μs)	T_{off} (mu)	T_{off} (μs)	T_{off} (mu)	T_{off} (μs)
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

Legend: T_{off}- Pulse off time, mu- machine units, μs- micro seconds

Table C: Conversional table for wire tension from machine units (mu) to grams (gram)

WT (mu)	WT (gram)	WT (mu)	WT (gram)	WT (mu)	WT (gram)	WT (mu)	WT (gram)
0	450	4	500	8	1000	12	1800
1	450	5	600	9	1200	13	2000
2	450	6	700	10	1400	14	2200
3	450	7	850	11	1600	15	2500

Legend: WT- Wire Tension, mu- machine units, μ s- micro seconds