Investigation on surface integrity and material transfer of Ti-6Al-7Nb alloy in die-sinking EDM Process

A dissertation submitted in partial fulfilment

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in

Production Engineering

by

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CERTIFICATE

Certified that the thesis entitled "Investigation on surface integrity and material transfer of Ti-6Al-7Nb alloy in Die-sinking EDM Process" which is being submitted by Krishna Kumar (Roll No.801482013) to the Department of "Mechanical Engineering, Thapar University, Patiala, Punjab" in partial fulfilment of the requirements for the award of the degree of Master of Engineering, (Production Engineering) is a record of bona-fide research work carried out by me under the guidance of Dr. Vinod Kumar Singla. The matter presented in this thesis has not been submitted in any other University or institute for the award of any other degree.

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ABSTRACT

Ti-6Al-7Nb is of medium strength among remaining alloys of Ti. It`s a surgical implant device. These alloys were specially developed for medical implant devices. It has very similar properties like Ti-6Al-4V. In this alloys vanadium has been replaced with niobium material. After replacing vanadium, this new alloy has got very unique feature that's more biocompatibility than old vanadium alloy and, it is nontoxic like Ti-6Al-4V.

The Die sinking electrical discharge machining processes has been found to be a good alternative of conventional machining processes, but there is lack of data and suitable models for predicting the performance of Die sinking EDM processes particularly for Ti-6Al-7Nb alloy.

In the Present work, Investigation on surface integrity and material transfer of Ti-6Al-7Nb alloy in Die-sinking EDM Process was done. The empirical modeling of process parameters of the Die sinking EDM has been carried out for the Ti-6Al-7Nb using a well known experimental design approach called response surface methodology(RSM). The parameters such as peak current, pulse-on, pulse-off and spark gap voltage have been selected as input variables keeping others constant. The performance has been measured in terms of MRR, TWR, SR, and MH

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LIST OF SYMBOLS AND ABBREVIATIONS

A	:	Ampere
SV	:	Spark Gap Voltage
Ton	:	Pulse on time
Toff	:	Pulse off time
V	:	Volt
Ip	:	Peak Current
µs	:	Micro Second
MRR	:	Metal removal rate
TWR	:	Tool wear ratio
SR	:	Surface roughness
MH	:	Micro hardness
BHN	:	Brinell hardness number
BBD	:	Box behnken design
CCD	:	Center composite design
C	:	Carbon
Fe	:	Ferrous
Avg.	:	Average
Apx	:	Approximate
Dia.	:	Diameter
DOE	:	Design of experiment
Dof	:	Degree of freedom
EDM	:	Electric discharge machine
mg	:	Mili-gram
Min	:	Minute

HV	:	Hardness (Vicker`s)
LOF	:	Lack of fit
n	:	Number of observation
Nb	:	Niobium
Al	:	Aluminium
Ti	:	Titanium
Ra	:	Average roughness
SEM	:	Scanning Electron Microscopy
XRD	:	Xray differaction
SF	:	Surface finish
Ta	:	Tantanum
SSPE	:	Sum of Squares of pure error
SSLOF	:	Sum of Squares of lack of fit
SSR	:	Sum of Squares regression
SSRES	:	Sum of Squares of residual
SST	:	Total Sum of Squares
WLT	:	White Layer Thickness
RL	:	Recast Layer
μ	:	Micro
Ω	:	Ohm
α	:	Significant level
β	:	Regression coefficients
$\sigma 2$	:	Variance
ε	:	Random error

CHAPTER 1
Introduction

1.1 Background of EDM

History of EDM starts from era of 1770 when it was first innovated by an English scientist Joseph Priestley. But utilization of electric discharge machining could not be done until 1943 because when it was developed by Joseph Priestly (1770), EDM Machining was very imprecise and punctured with failures.

When two scientists of Russia, B. R. Butinzky and N. I. Lazarenko jumped into this field with the task of controlling the erosion of Tungsten material but unfortunately they could not complete this task but they discovered very important thing regarding electric discharging machining that if electrode is being dipped or immersed inside the dielectric fluid then in that case erosion can be controlled more accurately and more precisely. This concept led him to develop new technology known as Die-sink electric discharge machining. Later on it got its usage in the industries. From the mid-1970 it was commercially used and wire EDM began to be a feasible technique that helped in shaping the material. In the mid-1980s.The EDM techniques were known as a machine tool. This exodus made EDM more easily and widely applicable over traditional machining processes.

With the growth of industries and new needs, requirement of new advance hard materials increased, which has better properties for heavy duty usage. New developments of techniques in the area of material science have pointed us to new composite materials, materials and ceramics having good thermal characteristics and mechanical properties as well as electrical conductivity so that they can easily be machined by spark erosion. With the development of new materials, the requirement of new techniques for machining increased as we know, they can not be machined with traditional methods of machining because of high hardness and poor machinability like Tungsten, Titanium and some other super alloys etc. So these kind of material can only be cut with the help of some non-tradition machining where tool does not touch the work-piece. Material is being cut with the utilization of non-conventional energy sources which is being utilized special machines, known as known conventional/ Non-traditional machining. These hard materials have their utilization in many fields such as aerospace, nuclear engineering and other industries. These materials have very low weight to strength ratio or in other words it has very high strength to weight ratio.

Generally Electric discharge machines cut electrically conductive materials like Titanium, Tungsten, some other super alloys but nowadays cutting composites and ceramics on Electric discharge machines is also feasible. The machining processes can be said non-traditional in the sense that they do not use traditional tools to remove metal, instead they utilize other forms of energy for cutting materials. Nowadays requirement of goods with good dimensional accuracy highly finished, and complex shape is high. The problems associated with complex shape, size and demand for product accuracy and surface finish can be achieved through non-traditional methods. Non-traditional processes acquire many capabilities but not volumetric material removal rate, for which great modifications have been made in the past few years to increase the MRR. As MRR increases, the cost decreases, stimulating uses of nontraditional process increases. The Electrical Discharge Machining (EDM) process is used widely for making dies, tools and other precision parts.

Electric Discharge Machines have replaced many other traditional machining process like milling, drilling, grinding, and many more operations. And it has established its own reputation for machining process in modern industrial world. And these are capable to cut hard in complex shape with high accuracy even while these materials have very poor machinability like tool steels (heat treated), super alloys, composites, carbides, steels (heat resistant), ceramics etc. These are used in die making industries, aeronautics, aerospace, and nuclear industries. Electric Discharge Machining has used in in many new fields like medical field as implant devices, sports, surgical, instruments, optical field and automotive R&D areas.

1.2 Introduction of EDM Process

Electro Discharge Machining (EDM) is a non-traditional, electro thermal process, electro thermal means electrical energy is being converted into thermal process for machining process. How conversion takes place, answer is simple, Electric Discharge Machines utilize electrical energy to convert it into sparks that contains very high thermal energy and with the help of such high energy material gets melted and evaporated that is material removal takes place.

Electric Discharge Machines are mainly used hard and difficult to machine materials. Electric Discharge Machines can cut very complex shapes and geometry to make dies etc. In Electric Discharge Machining, there is no need of hardening process to soften or harden the material.

This method can be used with any other metal or metal alloy such as titanium, hastelloy, kovar, and inconel. Also, applications of this process to shape polycrystalline diamond tools have been reported.

1.3 Principle of EDM Process

In Electric discharge machining process desired shape and geometry is achieved by material removal from the work-piece. Material removal takes place by erosion of material from work-piece and erosion occurs due to rapidly recurring spark (due to discharge) between the gap of work-piece and tool. A very thin gap is maintained between tool and work-piece with the help of servo motor. Both tool and work-piece are submerged into working fluid tank. Dielectric fluid breakdowns and restores itself between the gap of work-piece and tool electrode. When ions are released from tool towards work-piece it breakdowns the dielectric fluid into positive and negative ions and this is plasma is being created between tool and work-piece and when plasma collapse and sparks generates gap is created in between tool and work-piece, to fulfill the gap between work-piece and tool electrode new dielectric fluid enters in between the gap of tool and work-piece [1].

Natural Kerosene oil or Synthetic EDM Oil or De-ionized water are common dielectric fluid which are being used in EDM. There are two electrodes in EDM for machining operation one is connected to negative terminal of DC power supply while other one is to positive terminal. As we want to remove more material from work-piece than tool, so work-piece is made as anode while tool is as cathode. And power is supplied to both electrodes when voltage between the gap is sufficiently high, it generates plasma which collapse after a particular time and forms a spark and that time period is in micron. Formation of sparks happens in very less time (in microns). As plasma collapse high pressure develop between tool and work-piece, because of this high pressure between work-piece and tool electrode, high temperature is generated and such high temperature and pressure leads to melting and evaporation of material. This is how material is melted and eroded from work-piece.

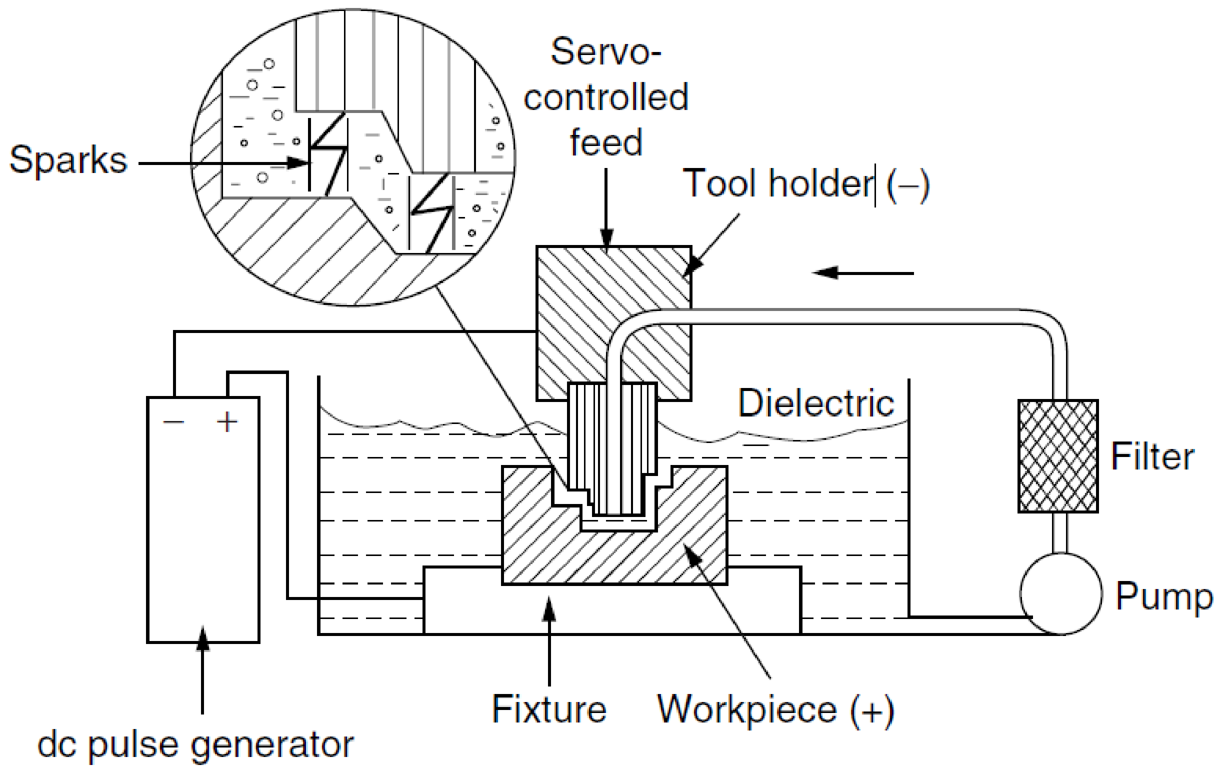


Fig 1.1 http://www.mechscience.comwp-contentuploads201408image1.png

Temperature rise in local region and this local temp. rise leads to removal of material. Material removal happens because of instant melting and vaporization of the material. The molten metal is removed partially. It can not be removed completely but only partially. Some molten material is being flushed away with the help of flushing but very little material re-solidifies at the machined surface and material which is being flushed that material goes in the form of spherical shape, known as debris. Molten material forms spherical shapes because it has lowest surface tension than others geometries like square, oval, or elliptical etc.

The time period till for which voltage is applied plasma channels forms and collapse and it generates shockwaves and this shockwave leads to evacuation of molten material but as soon as voltage is withdrawn there is no plasma and no pressure force.

1.4 Types of Electric discharge machines

Basically Electric discharge machines can be divided into two broad categories

1.4.1 Die-sinking EDM process
1.4.2 Wire-cut EDM process

1.4.1 Die-sinking EDM Process

In the Sinker type Electric Discharge Machining process, two electrodes are being submerged into a tank filled with an insulating liquid (dielectric fluid) and electrodes are connected to a DC power supply source and supplied power switches between on and off with the help of controller. When supply is on sparks generates and material removal takes place and the time period for which current supply is on is known as pulse on time and time period for which current is off is known as pulse off time. Since EDM removes material in volume and make cavity in the work-piece so it is also known as Volumetric EDM process or Cavity EDM process. EDM process consists of two electrodes (tool and work-piece) and they are submerged in an insulating liquid like traditional kerosene or synthetic EDM oil or Other dielectric fluids. The electrode and work-piece are connected to DC power supply. The power supply generates an electrical potential between the two parts. As the electrode approaches the work-piece, dielectric breakdown occurs in the fluid, forming a plasma channel, and a small spark jumps.[2]

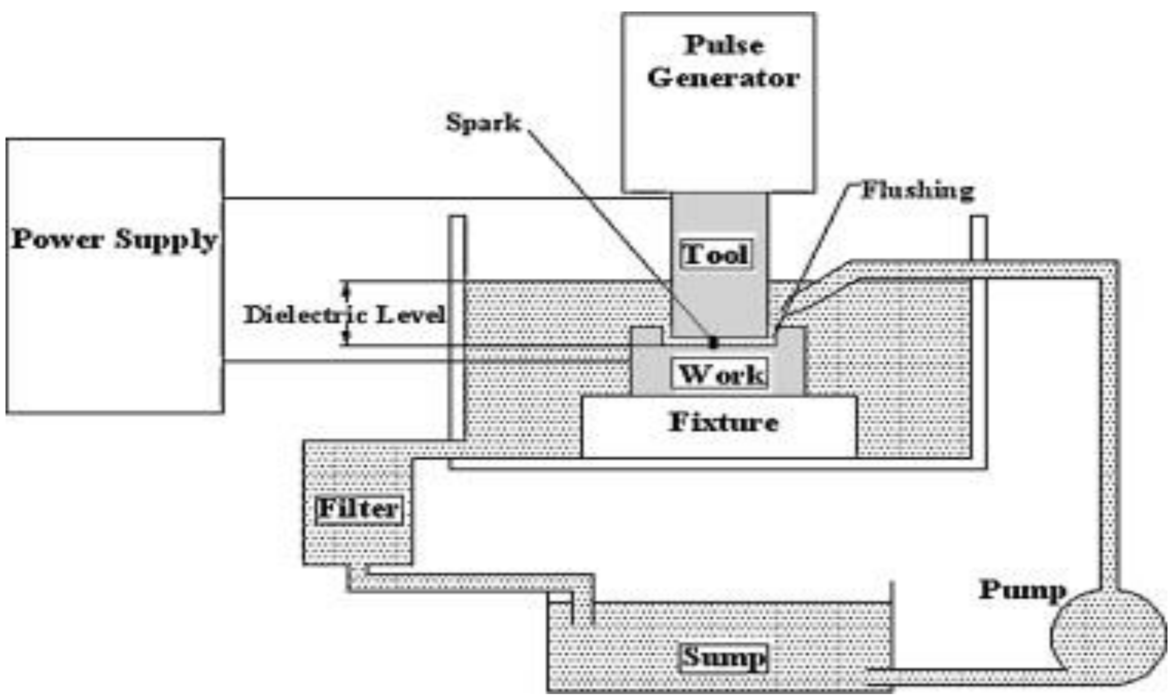


Fig 1.2 http://www.psep.ichemejournals.comcmsattachment20208160812040977411gr1.jpg

Since as we know spark generates at those points which are at closest distance so because of irregularities at surface, generally closest point are one or two. So These sparks collide one at a time because different closest in the gap between work-piece and tool are not same.

So spark to occurs simultaneously at all such locations. These sparks happen in very large numbers without gap with respect to time at random locations between the work-piece and tool electrode. As the base metal is eroded, and the spark gap subsequently increased, and electrode is lowered automatically with the help of servo motor installed in the machine so that the process can go on without any interruption. Thousands of sparks occur per second, with the actual duty cycle carefully controlled by the setup parameters.

1.4.2 Wire-cut EDM Process

Wire EDM is an electro thermal process in which a thin metal wire is used along with dielectric fluid which allows the water to cut the material of work-piece with the help of heat generated from spark. Dielectric fluid is to be non-conductive and generally Brass is being used as thin metal wire to cut the material. Since spark generates heat and cut the material that's why this process is also known as spark EDM. Wire is rolled on to two rolls which rotates into opposite direction to give feed of wire and as rolls rotates new position continuously comes in contact with the material this avoids the breaking of wire during cutting.

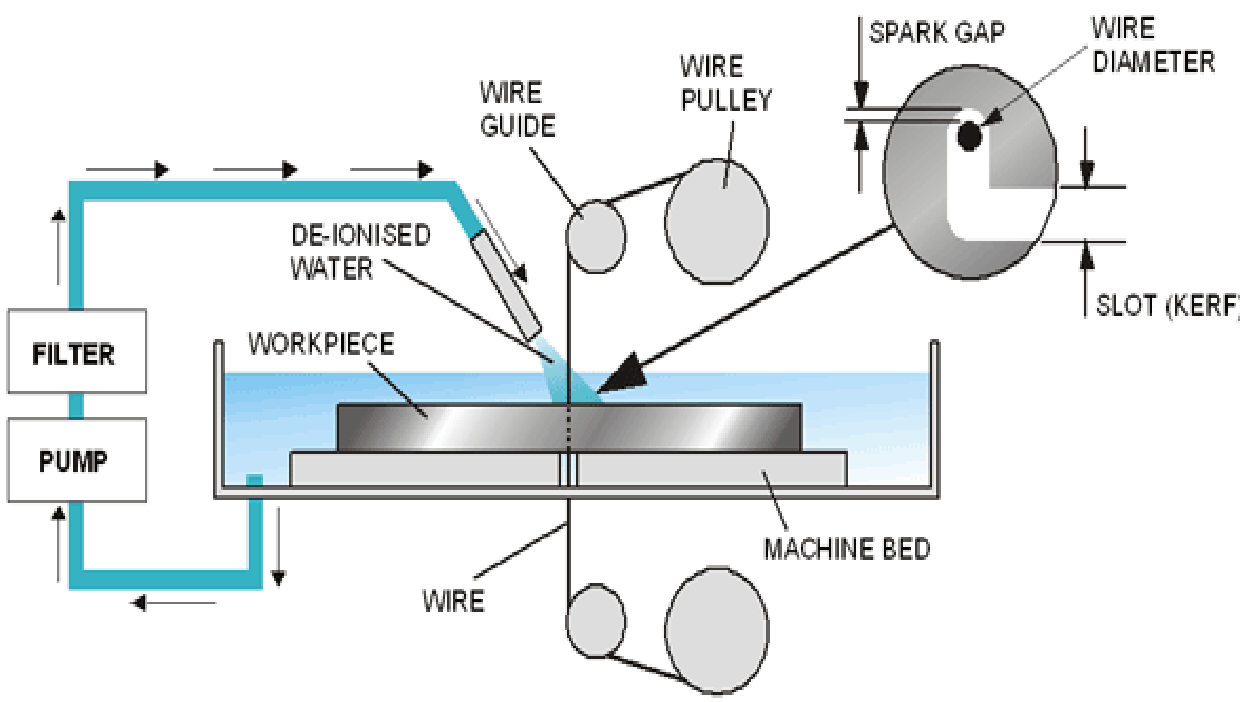


Fig 1.3 http://www.insinyoer.comwp-contentuploads201510WEDM_process.gif

Cutting pattern in wire EDM is generally controlled by CNC in which program is made and feed into the system and according to that wire follows the path and cut the desired geometry. Because of this programming feature, it makes EDM highly capable machining process. Any desired complex shape and geometry can be obtained. In wire EDM process one initial hole is to be made to cut material because through that hole wire will go in and then it will cut the material and will able to move accordingly.

Wire-cutting EDM is mostly used when low residual stresses are desired, because requirement of cutting force is low for metal removal so required power per unit pulse is low with respect to Die sinking EDM process, little change in the mechanical properties of a material occurs because of low residual stresses, Stress relieved material should be used else there are chances of distortion due to the inherent properties of the process, wire EDM can easily cut hard conductive materials in complex shape with precision.

1.5 Important parameters of EDM Process

(a) Pulse on time/ Spark on time (T_{on})

The time duration for which current is permitted to flow per cycle between tool and work-piece, is known as pulse on time or spark on time. This time duration is in micro-second. As time duration increase or decrease, the energy supplied will also increase or decrease and so will MRR. Because MRR is directly proportional to the energy supplied between tool and work-piece [3].

(b) Pulse off time/ Spark off time (T_{off})

The time duration for which current is not permitted to flow per cycle between tool and work-piece, is known as pulse off time or spark off time. This time duration permits the molten material to re-solidify on the machine surface as recast layer or between the tool and work-piece as debris. This time period also permit dielectric to washout the debris formed at eh gap between tool and work-piece. These parameters stabilize the process and avoid formation of arc [4].

(c) Arc gap or Spark gap

It's a gap between tool electrode and work-piece electrode. Its known as spark gap. This gap is maintained with the help of servo motor during cutting operation.

(d) Peak current/ Discharge current

Current is measured in amp Allowed to per cycle. Discharge current is directly proportional to the Material removal rate [5].

(e) Duty cycle (τ)

It's a percentage of pulse on with respect to total cycle time. And total cycle time is pulse on time plus pulse off time.

$$\tau = \frac{T_{ON}}{T_{ON}+T_{OFF}} \qquad \text{...1.1}$$

(f) Voltage (V)

It is a potential that can be measure by volt it is also effect to the material removal rate and allowed to per cycle.

(g) Diameter of electrode (D)

Tool (copper)of diameter 6 mm is used for experimentation. Its of simple cylindrical shape.

1.6 Characteristics of Electric Discharge Machines

Table 1.1 Technical Specification of EDM [6]

TECHNICAL SPECIFICATIONS	
Machine Tool	**Xepert1**
Work tank internal dimensions (W x D x H)	900 x 600 x 350 mm
Work table dimensions	600 x 400 mm
Longitudinal travel (X)	400 mm
Transverse travel (Y)	300 mm
Quill travel (Z)	300 mm
Max. workpiece height	250 kg
Max. permitted load on the table	1000 kg
Max. electrode weight	50kg - without 'C' axis 25kg - with 'C' axis (In static mode)
Pulse Generator	**e Pulse 50 CNC**
Pulse generator type	MOFSET
Maximum working time	50 A
Pulse on time	0.25 -3000 p/sec
Pulse frequency	0.22 kHz
Max MRR (Cu St)	350 mm^3 /min
Max MRR (Gr Steel)	500 mm^3/min
Best surface finish (Cu St)	0.3 Ra
Min. electrode wear (Cu St & Gr- St)	<0.2%
Power supply	3 phase, AC 415 V*, 50 Hz
Connected load	6KVA

1.7 Dielectric fluid

In 1943, two scientists of russia, Mr. and Mrs. B. R. and N.J. Lazarenko, explored that the erosion due to capacitor discharges could be used in the machining of materials. In first attempt, they used natural air as a dielectric fluid. But later on, it was clear, that derivatives of mineral oil had adequate advantages over natural air. And those advantages are higher disruptive strength, least spark gap, higher precision which could be used in machining. Spark frequency could be increased and metal particles could be removed without difficulty.

From 1960 onwards the mineral oil industry began developing industrial fluids specifically for use in spark erosion machines.

Fig 1.4 Dielectric Fluid (EDM 3001 Lite) [Global Industries, Patiala]

In EDM process material removal takes place due to melting and evaporation of material. Since it’s electro thermal process so this process must take place in the absence of oxygen so that oxidation would not take place at the surface of material. Because oxidation has its several disadvantage like poor surface conductivity. So Dielectric fluid must provide oxygen free environment and along with this property it should have high electrical resistance.

1.7.1 Functions of Dielectric fluid [7]

1.7.1.1 Insulation

Insulating the tool electrode and work-piece is important and dielectric fluid helps in insulation. Disruptive discharge occurs across a narrow spark gap. With the help of insulation, efficiency and accuracy increased.

1.7.1.2 Ionization

To achieve optimum condition in machining of EDM process, right path should be provided to the generated electrical field. After providing the path, impulse occurs and that impulse must deionize so that next spark can occur. To achieve high energy density, dielectric must circumscribe the spark path which will help in increasing the discharge efficiency.

1.7.1.3 Cooling

Temperature if one spark is around 8,000-12,000° C when it erodes the work-piece. Dielectric fluid cools both the electrodes (tool electrode and the work-piece). Overheating of the electrode causes high electrode wear, which should not happen.

1.7.1.4 Removal of waste particles

Metal particles that have been eroded away must be removed from the area of erosion by the dielectric to avoid disruptions in the process.

1.7.2 Requirements for Dielectric

If we think from theory point of view, all fluid which are insulated, can be used as dielectric fluid. But, it`s not feasible, so only synthetic oil or de-ionized water and natural hydrocarbons are used as dielectric fluid nowadays. Production of these hydrocarbons can be done by distillation and refining of mineral oil, or synthetic process can be used by processing gases in a synthetizing oven in the presence of a catalyst. Hydrocarbons produced by synthetic process are characterized by unparalleled purity. In addition, precisely those chains of hydrocarbon molecules can be synthetized which have the best possible erosive effect as well as offering optimum protection against electrode wear. This way, they have far better properties over those mineral oil products which are produced from certain mineral oil [7].

1.7.3 Criteria for assessing Dielectrics

The following criteria are generally used today to assess different dielectric fluids

(a) Degree of metal removal and electrode wear

(b) Flash point

(c) Density

(d) Viscosity

(e) Conductivity

(f) Particle Suspension

(g) Dielectric constant

(h) Smoke

(i) Compatibility with other machine component like sealing, materials engine parts

(j) Aging stability

(k) Availability

(l) Effects on health

(1) Toxicity

(2) Filterability

(3) Skin irritation

(4) Odours

(m) Price

1.8 Flushing method during spark erosion

Fig 1.5 Nozzle For Open Flushing [Global Industries, Patiala]

Flushing has its advantage in EDM process. When machining operation goes on debris comes at the gap between work-piece electrode and tool electrode, if gap is filled with debris particles, arc will form instead of spark. So we have to avoid arc generation for that debris has to be replaced with new and fresh dielectric fluid so that there will always be spark not arc. Flushing introduces new clean dielectric fluid in the gap between work-piece electrode and tool electrode.

1.8.1 Type of Flushing methods

1.8.1.1 Open flushing

It`s very common type of flushing method and it is used if and only if, it is not possible to do boring of flush.

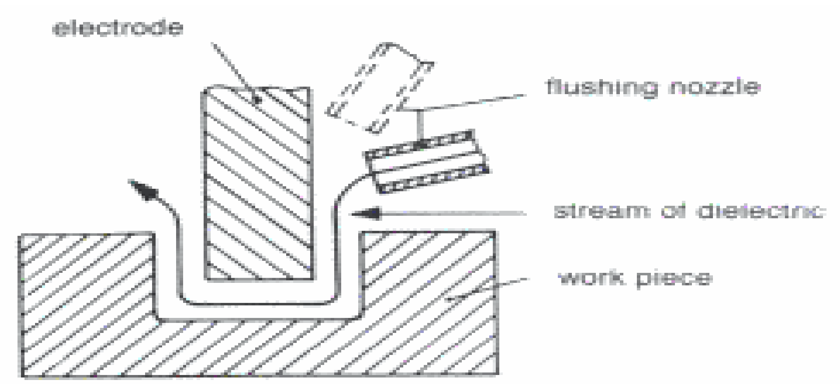


Fig 1.6 http://www.edmproducts.com/Dielectrics/ifase/ifase_5.htm

1.8.1.2 Pressure flushing

In this form of flushing method, Dielectric can be pushed through hole but in two way either through hole in the tool electrode or in work-piece. Amount of flow of dielectric fluid is most important thing for proper flushing.

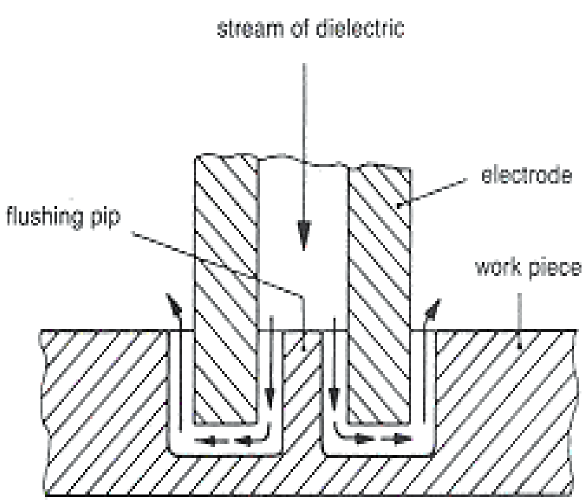


Fig. 2. Pressure flushing through the electrode

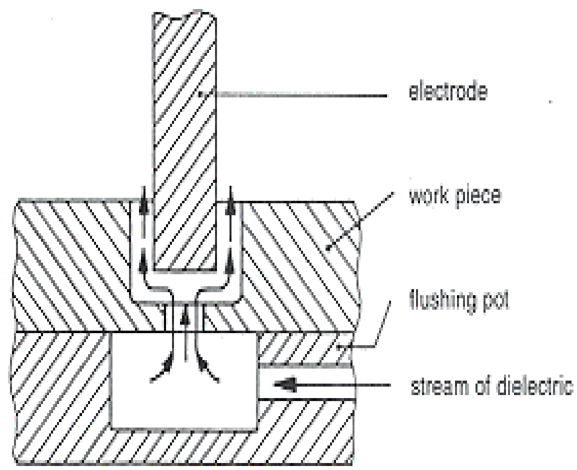


Fig. 3. Pressure flushing through the work piece

Fig 1.7 (http://www.edm-products.com/Dielectrics/ifase/images18-1.gif)

Fig 1.8 (http://www.edm-products.com/Dielectrics/ifase/images18-2.gif)

1.8.1.3 Suction Flushing

As term defines itself, particles which are eroded are sucked out of gap between work-piece electrode and tool electrode. This one best flushing method, where good surface finish or low surface roughness is main criteria. Since in die sinker type EDM process available gap is very narrow so it should be keep in mind that supplied dielectric is in sufficient quantity during machining for a stable process.

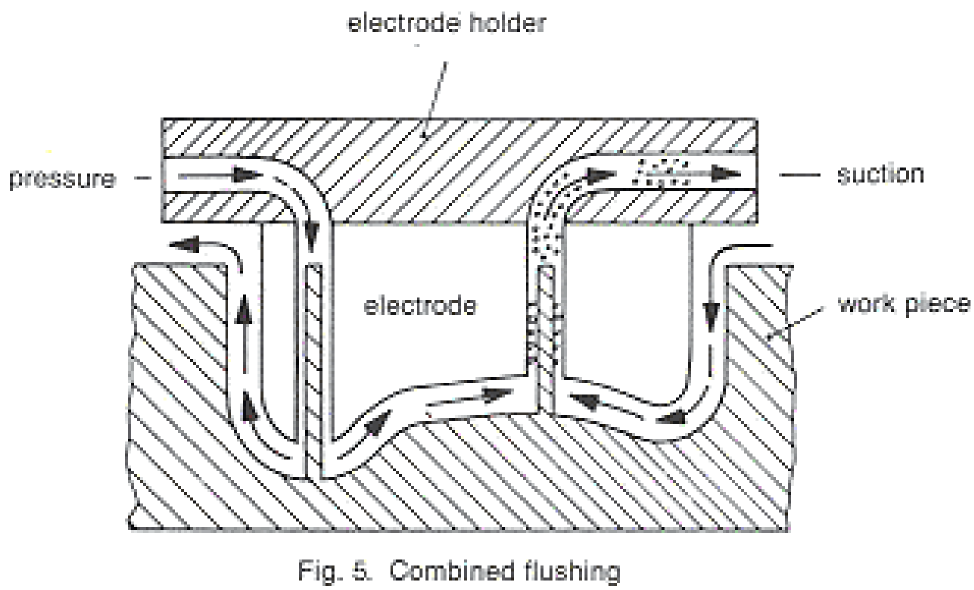


Fig 1.9 http://www.edmproducts.com/Dielectrics/ifase/images/18-3.gif

1.8.1.4 Combined flushing

suction plus pressure flushing is known as combined flushing and it`s being used in very complex shape machining process.

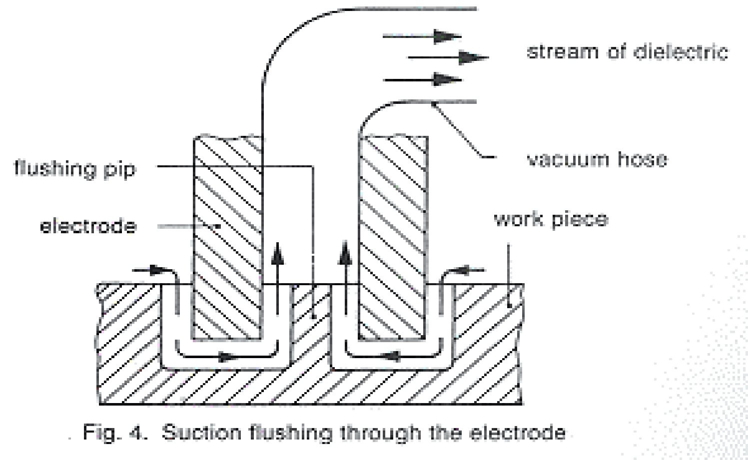


Fig 1.10 (http://www.edmproducts.com/Dielectrics/ifase/images/19-1.gif)

1.8.1.5 Interval flushing

In this kind of process, process does not take place continuously but its interrupted type machining process. Which improves the flushing during machining process. Backward and forth motion of the electrode works as suction and pumping respectively, which improves the effectiveness of the flushing process. When deep cutting or thin electrodes are involved in machining, then it`s very useful and also in finishing work.

1.8.2 Filtering the Dielectric

To achieve the better flushing in the machining, it is desirable that dielectric fluid must be clean. It should not have impurities. During machining process debris particles forms in the tank and sometimes they are the reason behind arcing so they must be filtered to avoid arcing etc. Additionally, the dielectric heats up during machining so it has to be cooled down again for normal working and temperature range lies between 20° C - 300° C. If temperature of dielectric is beyond limit, there will be inaccuracies in the work and evaporation rate of dielectric fluid will increase and loss of dielectric will be high. That’s why filtering is used in every EDM, which has the following functions to perform.

(a) Cooling the dielectric

(b) Cleaning the dirty dielectric coming from the work tank

(c) Providing the required amount of clean fluid

(d) Storing the dielectric

(e) Processing backwashed fluid and filtrate

1.9. Tool Material

Most important desired property of tool material is that Tool wear should not be high. When it comes under collision of positive ion. Hence localized temperature rise should be low by properly choosing its property. If temperature rises, even in that scenario, tool material must melt less. Further, the tool should be easily workable as intricate shaped geometric features are machined in EDM [3]. Thus the basic characteristics of electrode materials are:

1. Easy manufacturability
2. High thermal conductivity
3. High melting point
4. Higher density
5. High electrical conductivity
6. Cost – cheap.

The followings are the different electrode materials which are used commonly in the industry:

1. Graphite
2. Copper
3. Tellurium copper – 99% Cu + 0.5% tellurium
4. Brass

Here, In this experiment, Cu electrode tool of cylindrical shape (6mm dia.) with open type flushing system is used.

1.10. Design variables

Process parameters and response variables, and constant parameters are as follows

(1) Process Parameters

(a) Pulse on time
(b) Pulse off time
(c) Peak current
(d) Spark gap voltage

(2) Response variables

(a) Metal removal rate (MRR)

(b) Tool wear rate (TWR)

(c) Surface roughness (SR)

(d) Micro-Hardness (MH)

(3) Constant Parameters

(a) Spark gap

(b) Tool material

(c) Work-piece material

(d) Working environment

(e) Operator

1.11 Work-piece material

Electric discharge machine is able to cut difficult to machine or hard materials whose machinability is poor like Composites, super alloys, heat treated tool steel, ceramics, carbides etc. It`s capable to cut complex geometry with very good precision and accuracy along with maintaining the tolerance limit.

Different kind of Titanium and its alloys are being machined on EDM for different applications. Ti-6Al-7Nb is of medium strength among remaining alloys of Ti. It`s a surgical implant device. These alloys were specially developed for medical implant devices. It has very similar properties like Ti-6Al-4V. In this alloys vanadium has been replaced with niobium material. After replacing vanadium, this new alloy has got very unique feature that's more biocompatibility than old vanadium alloy other advantage, it is nontoxic like Ti-6Al-4V. To make Ti-6Al-7Nb alloy for medical implant, special procedure has to follow during manufacturing of this alloy. Heat treatment should be done that's annealing for 1 hour at 700 degree centigrade in air.

It was first discovered in 1977. It`s an alpha beta alloy of titanium. It has better mechanical properties, higher corrosion resistance and nontoxic. The main difference between Ti-6AL-4V and Ti—6Al—7Nb is related to different factors such as solid-solution strengthening, the structure-refining strengthening provided by the refined two-phase structure and the difference in the microstructure between the two alloys.[8]

Properties

Mechanical properties of Ti-6Al-7Nb are as follows[8]

Table 1.2 Mechanical Properties of Work-piece

Property	Minimum Value	Maximum Value	Unit
Density	4.51	4.53	g/cm^3
Hardness	2700	2900	MPa
Melting point	1800	1860	K
Specific Heat	540	560	J/Kg*K
Elastic Limit	895	905	MPa
Energy Content	750	1250	MJ/Kg
Latent heat of fusion	360	370	KJ/Kg

1.12 Applications of EDM Process

(1) In mold making tool and die industries, prototype and parts, aerospace, automobile and electronics industries.

(2) In machining of hard materials with poor machinability like tool steels, super alloys, titanium, tungsten carbides etc.

(3) Higher Tolerance limits can be obtained in EDM machining.

(4) In drilling of curved holes.

(5) For internal thread cutting and helical gear cutting.

(6) In machining sharp edges and corners

(7) In the field of sports, medical and surgical, instruments, optical, including automotive R&D areas.

(8) Ceramic materials that are difficult to machine can be machined by the EDM machining process.

1.13 Advantages of EDM Process

(a) Electrically conductive materials can be cut using the EDM process.

(b) Hardened work-piece can be machined.

(c) Complex profile can be cut by movement of head in X, Y, Z direction, controlled by NC programming

(d) Dies with complex shape can be machined easily.

(e) Automation

(f) Forces are produced by the EDM-process and that, as already mentioned, flushing and hydraulic forces may become large for some work piece geometry. The large cutting forces of the mechanical materials removal processes, however, remain absent.

(g) Thin fragile sections such as webs or fins can be easily machined without deforming the part.

1.14 Limitations of EDM Process

(a) The need for electrical conductivity – To be able to create discharges, the work piece has to be electrically conductive. Isolators, like plastics, glass and most ceramics, cannot be machined by EDM, although some exception like for example diamond is known. Machining of partial conductors like Si semi-conductors, partially conductive ceramics and even glass is also possible.

(b) Predictability of the gap - The dimensions of the gap are not always easily predictable, especially with intricate work piece geometry. In these cases, the flushing conditions and the contamination state of differ from the specified one. In the case of die-sinking EDM, the tool wear also contributes to a deviation of the desired work piece geometry and it could reduce the achievable accuracy. Intermediate measuring of the work piece or some preliminary tests can often solve the problems.

(c) Low material removal rate- The material removal of the EDM-process is rather low, especially in the case of die-sinking EDM where the total volume of a cavity has to be removed by melting and evaporating the metal. With wire-EDM only the outline of the desired work piece shape has to be machined. Due to the low material removal rate, EDM is principally limited to the production of small series although some specific mass production applications are known.

(d) Optimization of the electrical parameters - The choice of the electrical parameters of the EDM-process depends largely on the material combination of electrode and work piece and

EDM manufactures only supply these parameters for a limited amount of material combinations. When machining special alloys, the user has to develop his own technology.

Chapter 3

Literature Review

Here, few papers have been chosen for literature review, which are related to my research work like optimization of process parameters for different response variables, surface integrity of machined surface and surface topography, tool and work-piece.

(1) Marc Long et al. (1998) This paper represent the study which are done on titanium and its alloy which are compatible in biomedical field. When we compare with stainless steels and cobalt-based alloys, Titanium alloys have lower modulus, superior biocompatibility and enhanced corrosion resistance that is why these are being used as biomaterials. They are α and α+β alloys. New development in Ti alloys and composites are done which are metastable β alloys. They possess enhanced biocompatibility, improved modulus of elasticity, corrosion resistance better strain resistance and fatigue resistance but shear strength and wear resistance are drawback of Ti alloys which limits the application in orthopedic field. Β Ti alloys promised better wear resistance than α+β. New titanium alloy Ti-6Al-7Nb were developed for biomedical applications which can replace Ti-6Al-4V, having similar property except its non-toxic which has very positive impact [9].

(2) Oh-Seong Kwon et al. (2006) Experimentation was to done to investigate the surface property and cell toxicity of Ti-6Al-4V and Ti-6Al-7Nb after hydrothermal treatment. Bioactivity was studied at the surface of specimen planted in body. Specimen was implanted in body for 30 days and then toxicity was calculated based on optical density of cells survived after these many days. This method is a used to improve the surface activation (oxidation energy) and oseo-synthesis when a device is implanted and it sets in bone by absorbing Ca and P from body, which exist in the electrolyte solution. Oxide (TiO2) films were formed on all specimen by anodic oxidation and it is composed of strong anatase peaks without rutile peaks. And it was found that Ti-6Al-4V contained weak anatase peaks with weak rutile peaks while Ti-6Al-7Nb contained strong anatase peaks with weak rutile peaks. The surface activation layers forms only on the oxide films of Ti-6Al-7Nb alloy because of strong anatase peaks, also this alloy presented a significantly higher optical density than Ti and Ti-6Al-4V alloy on the MTT assay for cell toxicity evaluation [10].

(3) Ian R. Pashby et al. (2003) Literature survey reveals that oil based fluid or synthetic EDM oil can replace the natural hydrocarbon oil, which are more environmental friendly and more productive and provide better quality. It was seen that in sinker type EDM, organic oil was more efficient than deionized water. But if Organic compounds are being added to the water, MRR is higher than hydrocarbon oil for roughing and finishing operation both, In terms of surface integrity and surface roughness, SR and SI completely dependent on dielectric fluid. SR obtained from deionized water is lower than organic fluid while in SI carbon content found from experiments with organic fluid was higher than deionized water which results in increase in micro-hardness of recast layer. But cracks formed in machining with deionized water were little higher than in organic fluid [11].

(4) B. B. Pradhan et al. (2008) In this paper, a attempt is made to optimize the process parameters of micro-EDM process for Ti-6Al-4V. And for optimization MRR, TWR, Over-cut, Taper were chosen as response variable for evaluation with the help of taguchi method and Anova was applied to know about significant parameter and their interactions while peak current, pulse on time, duty ratio and flushing ratio were chosen as process parameters. And it was found that MRR and over cut increased as peak current and pulse on increases but after a certain limit or value MRR started to decrease because of formation of TiC which is bad conductor. TWR also increased with increase in pulse on time and peak current because of high discharge energy.

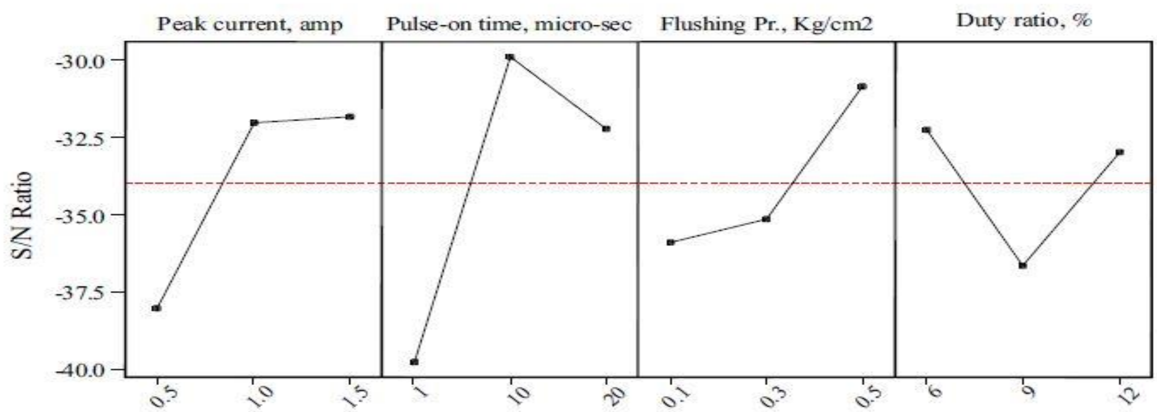


Fig 2.1 [4]

Effect of various parameters on recast layer or white layer was also considered. And it was seen that Thickness of the white layer formed on the machined surface contains micro-holes which increases sharply with increase in Ip and Ton [12].

(5) Yang Shen et al. (2013) In this paper, the energy distribution during Electric discharge machining of Ti–6Al–4V has been investigated at different parameters like spark gap, electrode polarity, pulse duration and electrode shape. The energy distributed into the work-piece is greatly affected by the gap distance. The energy distributed into both of the anode and cathode decreases with increasing gap distance because plasma diameter increases with increase in inter electrode diameter, as plasma diameter increase energy density decreases. The amount of energy distribution ratio decreases steadily with increasing pulse duration regardless of the polarity. More energy is distributed into the anode than into the cathode due to the difference of the plasma diameter [13].

(6) S. Prabhu et al. (2014) This paper`s concentration was on the investigation of the surface characteristics of AISI D2 Tool Steel and graphite was used as tool electrode during EDM process. The dielectric was mixed with carbon nanotube to see the effect on the surface roughness and micro-cracks. Response surface model (RSM) was developed to predict the surface roughness for combinations of EDM parameters. Analysis of variance and F test have been used to check the validity of response surface model and determine the significant process parameter affecting the surface roughness [14].

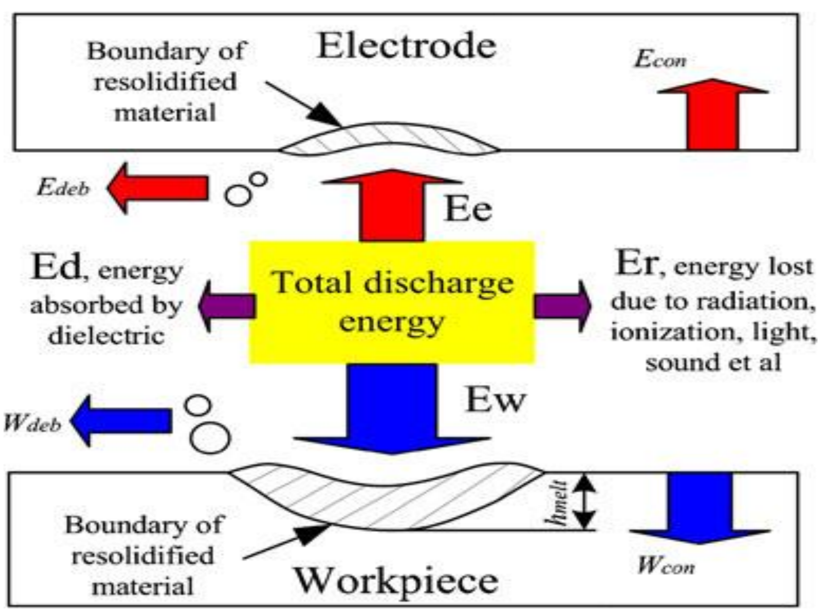


Fig 2.2 [6]

(7) Md. Ashikur Rahman Khan (2013) Study has been done on surface characteristics of machined surface in EDM on Ti-5Al-2.5Sn. Peak current, gap voltage, Pulse on time, and three tool electrode material (Graphite, Copper, Copper tungsten) were chosen as process parameters. Designing of experiment was done by Central Composite Design (CCD). And it was seen that surface energy increases with increase in peak current for copper and copper tungsten as tool electrode but in case of graphite SR was poor among all but above 22A peak current SR started to decreases and it gave best SR above 22A among all. As Pulse on time increased SR also increased but up to a certain value after that it remains constant for copper and copper tungsten but in case of graphite it starts to decrease. For Pulse off time SR decreases with increase of Pulse off time but after a certain value it starts to increase. SR decreases with increase in servo voltage for all tool material. Among three tool electrode it was seen that at low discharge energy, graphite delivers worst surface characteristics while copper–tungsten electrode produced the finest surface structure whilst [15].

(8) M. P. Garg et al. (2014) This paper tried to identify those process parameters which affects the response variable (cutting speed, SR) which are not included till now among research papers and along with this process parameters were also optimized. BBD was used to design the experiment and RSM was used for analysis purpose. pulse off time, Pulse on time, gap voltage, peak current, wire feed speed, wire tension were chosen as process parameter. Pulse off time (T_{OFF}), Pulse on time (T_{ON}), peak current (I_P), SV, and two-factor Interaction between T_{ON} and T_{OFF}, T_{ON} and SV, T_{OFF} and SV, SV and WT affected the cutting speed most. Wire feed and Wire tension had no considerable effect on cutting speed. Cutting speed was increasing with decrease in Toff and increase in Ton and SV due to higher discharge energy generated in the machining. Pulse off time (Toff), pulse on time (Ton), peak current (Ip), SV, WF and WT as well as interaction effects between TON and WT, IP and WF had main effect on SR. Wire feed had less impact on surface roughness (SR) but its interaction with peak current (Ip) showed a considerable effect on the same[16].

(9) Anish Kumar et al. (2013) In this paper investigation was done titanium of grade 2 by varying pulse off time, pulse on time, peak current, spark gap voltage, wire tension and wire feed and effect of process parameters was seen on metal removal rate (MRR), surface roughness (SR), wire wear ratio and dimensional deviation (DD) in WEDM process using RSM. Responses variables were optimized using multi objective response optimization. The Analysis of variance was applied to identify the significance of developed model. Experimental planning was done with the help of Box Behnken Design (BBD). It was observed that pulse off time and peak current and its interaction are most significant factors for MRR. Ton, pulse off time, spark gap voltage, peak current and interaction of Ton and peak current are significant factors for surface roughness. Zinc, carbon and copper were detected on machined surface using EDX analysis. Wire was ruptured because of high peak current. It was seen that pulse on time and peak current defines the integrity of machined samples and responsible for formation of deep craters, globules of debris and micro cracks and pockmarks. The cracks were observed due to high pulse on time and peak current [17].

(10) Anish Kumar et al. (2013) This article was mainly focused on microstructural analysis using EDX, SEM, XRD by changing the process parameters like pulse off time, pulse on time, peak current, spark gap. And it was observed that pulse off time, pulse on time and peak current are most responsible process parameters for surface integrity of machined surface which contains deep craters, globules of debris and micro cracks and pockmarks. Higher pulse on time and peak current results in formation of deeper and larger craters means poor surface. RL was formed due to low pulse off time, high pulse on time and high peak current. Micro cracks were developed in RL because of high discharge energy. Micro cracks formation occurs due to rapid cooling and subsequently rapid heating during machining operation. Zinc, carbon and copper material were detected on the machined surface and it was seen by EDX [18].

(11) Muhammad Azam1 et al. (2016) Experimentation was done on WEDM on determine process parameters(pulse on time, pulse ratio, spark gap voltage, peak current and wire speed) which contributes in formation of recast layer. ANOVA method was applied for analysis purpose and it was found that pulse on time and wire speed are two significant parameters which affects the RL most. Craters, micro-voids, globules affects surface morphology most. Three surface layers (RL, HAZ, base material) were formed which can be easily seen with the help of SEM 19].

(12) Yanzhen Zhang et al. (2011) Every EDM process forms a RL on the machined surface whose properties depend on dielectric fluid used in machining. Water in oil type dielectric fluid was used and obtained characteristics using XRD, SEM, EDS from it, and were compared with characteristics obtained from kerosene and deionized water. It was found that both carbide and oxide are present in w/o emulsion as dielectric while only carbides were present in kerosene as dielectric. And higher SR and more micro voids were detected in w/o emulsion than in kerosene. But cracks formed in w/o emulsion was of lesser depth and lesser length than in kerosene.

(13) Shy-Feng Hsieh et al. (2011) Effects of the composition of the TiNi/TiNb-based alloys and electrical discharge machining (EDM) parameters on the properties of the materials were investigated. Ti, Ni, Mo based alloy and Ti, Nb based alloy reduced the MRR, TWR, while increased the SR and RL in EDM. Higher current and pulse on time provides higher MRR. Deionized water was used as dielectric fluid. EDMed surface showed higher hardness than un machined surface because of formation of oxide. Electric discharge machined surface have higher biocompatibility because of the presence of TiO_2 [20]

Chapter 3

Experimental Work

Introduction

Here in this section, we are going to discuss about the experimental work in which, designing of experiments is done by Box Behnken Designing method with the help of Design Expert (version-6.08) software. Box Behnken designing method is more effective from reducing number of experiment point of view and is more effective too. It helps in doing smart work. After designing the experiment ANOVA method is applied for analysis purpose. Selection of work-piece and tool electrode was first thing to do. Here Ti-6Al-7Nb is selected as work-piece material and copper as tool electrode for experimentation after that range of process parameter was defined for experimentation. It was decided after conducting pilot experiment. And then designing was done with the help of BBD [22].

Four parameters were selected as input parameters which are, Pulse off time, Pulse on time, Peak current, Spark gap voltage. And four parameters were selected as response variables which are, MRR, TWR, SR, MH.

3.1 Experimental set up

Experimental work was done on Electric discharge machine (Electronica Xpert-1, CNC type). It's a die sinker type EDM machine in which constant gap is maintained with the help of servo motor while programming is done on advance in built software GURU. Positive polarity was given to work-piece while negative to tool electrode. This EDM used synthetic oil known as EDM 3001 lite. Here open type flushing is used for experiments. While copper of cylindrical shape with 6mm diameter is used to make a hole in work-piece which is in disc form with 10 mm diameter. For all experiments energy is being supplied for 30 minutes and after this response variables MRR, SR, TWR, MH are being observed. While doing these experiments there are four input variables Pulse off time, Pulse on time, Peak current, Spark gap voltage are varied each with three levels.

Die sinker type Electronica Xpert-1 machine consists of following major parts

Fig 3.1 Die Sink EDM Model Electronica Xpert-1 [Global Industries, Patiala]

3.1.1 Reservoir for dielectric fluid, pump and circulation system.

3.1.2 Tool head

3.1.3 Power generator and control unit

3.1.4 Working tank with job holding device

3.1.5 Tool holder

3.1.6 The servo system to feed the tool

3.1.1 Reservoir for dielectric fluid and pump

As word defines reservoir means storage, here reservoir is used to store the dielectric fluid and give supply for each run of experiment. Experiment is being conducted and then drained back to reservoir so that it can avoid contamination in the EDM oil. EDM oil goes back to reservoir via filters so that debris particles or any other foreign particles can be filtered. And whenever there is requirement of EDM oil in machine for machining purpose it is being pumped into working tank with the help of pump.

3.1.2 Tool head

Tool head holds the device and move the tool in the feed direction and it maintain the gap between tool and work-piece with the help of servo motor. Gap may be predefined in the program or it may vary according to need. It can move in X, Y, Z direction from the company defined origin point. This origin point is defined by the dimension of tank and working table.

3.1.3 Power generator and control unit

First control unit controls the time duration for which current is being supplied for each pulse, it`s also known as pulse on time. After that is controls the amount of current flow that is permitted for each pulse. Pulse time duration is of very short time duration, it`s in micro-seconds.

This is how it controls the amount of energy consumption for each cycle in electric discharge machining. And energy consumption controls the MRR. Minimum current and minimum pulse on time equal to minimum energy consumption means minimum MRR while maximum pulse on time and maximum peak current equal to maximum energy consumption means maximum MRR.

Control unit is installed to control the functions of machining parameters like pulse off time, pulse on time, spark gap voltage, spark gap, and maintaining the spark gap.

3.1.4 Working tank with job holding device

Working tank stores the EDM oil for machining operation. Tool and work-piece are being sink into the EDM oil for proper machining. This working tank contains the jigs and fixture to hold the work-piece or job. So that job will not move from its place during machining operation.

3.1.5 Tool holder

Tool holder is situated at the bottom phase of tool head. Tool holder holds the tool electrode tightly.

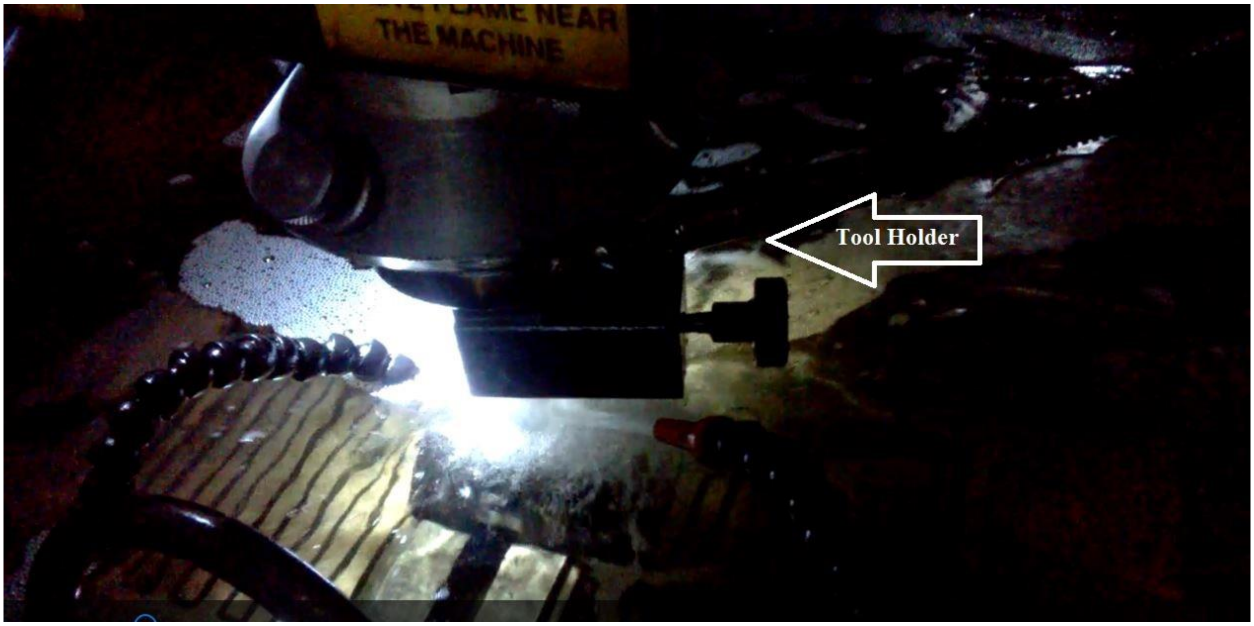


Fig 3.2 Tool Holder [Global Industries, Patiala]

3.1.6 The servo system to feed the tool

The servo control unit is install to control and maintain it to the given gap. It measures the gap voltage and comparison is done with the present value of voltage and then difference in voltage is measured, and is used to control the feed of head with the help of servo motor to adjust the gap.

3.1.7 Process parameters values and specifications of EDM Process

Process parameters values and specification of EDM

Table 3.1 Specifications of EDM Process

Mechanism	Erosion with the help of series of sparks
Spark gap	0.4 mm
Peak current	7-15 A
Pulse on time	500-1000 μs
Pulse off time	10-20 μs
Peak voltage across the gap	90-150 V
Dielectric fluid	EDM 3001
Tool material	Copper
Materials that can be machined	All metals which are conducting
Shapes	Slots, Complex geometry, Micro-holes,
Limitations	High specific energy consumption, Low MRR

3.2 Selection of the work piece

Electric discharge machine is able to cut difficult to machine or hard materials whose machinability is poor like Composites, super alloys, heat treated tool steel, ceramics, carbides etc. It`s capable to cut complex geometry with very good precision and accuracy along with maintaining the tolerance limit.

Different kind of Titanium and its alloys are being machined on EDM for different applications. Ti-6Al-7Nb is of medium strength among remaining alloys of Ti. It`s a surgical implant device. These alloys were specially developed for medical implant devices. It has very similar properties like Ti-6Al-4V. In this alloys vanadium has been replaced with niobium material. After replacing vanadium, this new alloy has got very unique feature that's more biocompatibility than old vanadium alloy other advantage, it is nontoxic like Ti-6Al-4V. To make Ti-6Al-7Nb alloy for medical implant, special procedure has to follow during manufacturing of this alloy. Heat treatment should be done that's annealing for 1 hour at 700 degree centigrade in air.

It was first discovered in 1977. It`s an alpha beta alloy of titanium. It has better mechanical properties, higher corrosion resistance and nontoxic.

3.2.1 Chemical composition of work-piece (Ti-6Al-7Nb)

Table 3.2 Chemical Composition Of Work-piece

Ti	Al	Nb	Fe	C	N	O	H	Ta
Remainder	6.3	7.2	0.04	0.02	0.01	0.09	0.001	<0.01

3.2.2 Mechanical Properties of Ti-6Al-7Nb

Table 3.3 Mechanical Properties of Work-piece [23]

Property	Min. Value (S.I.)	Max. Value (S.I.)	Unit (S.I.)
Density	4.51	4.53	Mg/m^3
Bulk Modulus	111	142	GPa
Compressive strength	1074	1086	MPa
Ductility	0.1	0.15	
Elastic limit	895	905	MPa
Hardness	2700	2900	MPa
Poisson`s ratio	0.35	0.37	
Shear modulus	36	41	GPa
Tensile strength	995	1005	MPa
Young`s modulus	100	110	GPa

3.2.3 Thermal Properties of Ti-6Al-7Nb

Table 3.4 Thermal Properties of Work-piece [23]

Property	Min. Value (S.I.)	Max. Value (S.I.)	Unit (S.I.)
Latent heat of fusion	360	370	KJ/Kg
Melting point	1800	1860	K
Specific heat	540	560	J/Kg.K
Thermal conductivity	7	8	W/m.K
Thermal expansion	8	9.8	10^{-6} /K
Resistivity	126	158	10^{-8} ohm.m

3.2.4 Preparation of work-piece

I got Ti-6Al-7Nb alloy in the form of rod whose diameter was 10mm and length was 1000mm. It was in three pieces. Material was cut in disc form whose diameter is same (10mm) but length was around 20mm. After cutting the material with the help of HSS blade, it was found that surface was very much uneven. So surface was made even with the help of belt grinder. We made one fixture to hold the disc because it was heating up too much.

Fig 3.3 Cylindrical shaped Work-piece [Thapar University, Patiala]

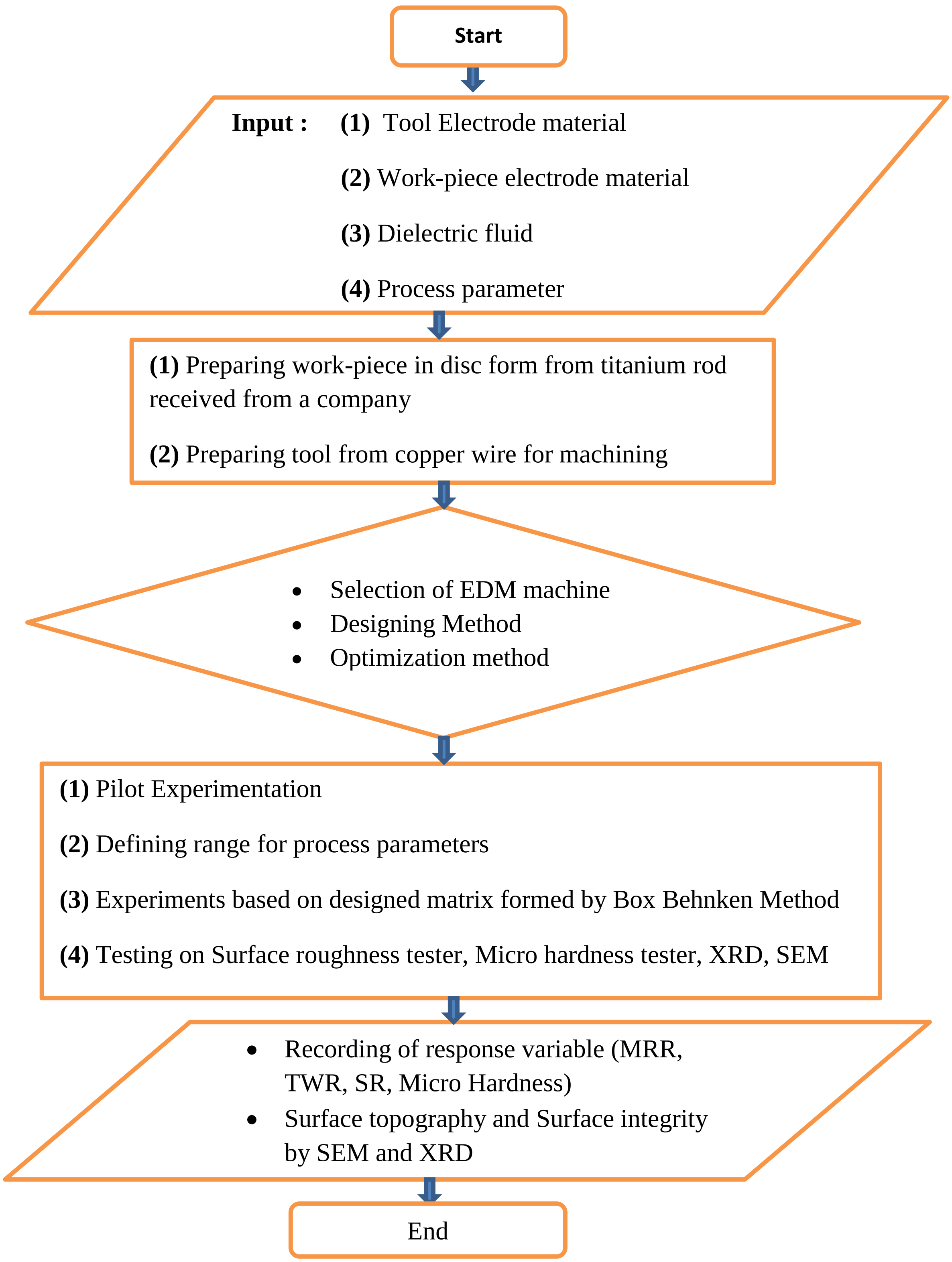
After making surface even on belt grinder, Surface grinder was used to make surface more smooth and flat.

3.3 Tool Design

Fig 3.4 Cylindrical shaped copper tool [Thapar University, Patiala]

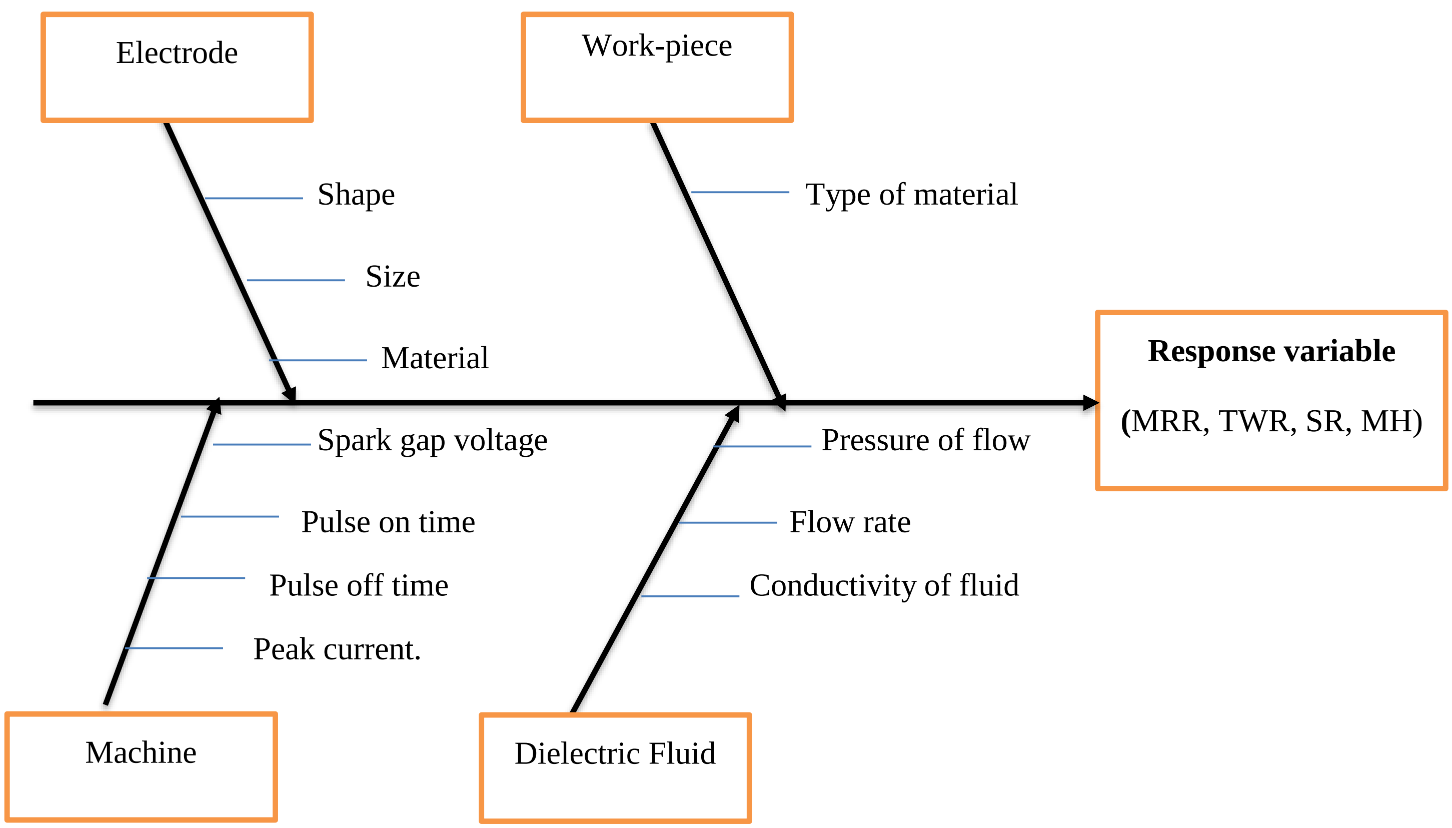
Machining operation is done to optimize the parameters not to make complex shape. So simple cylindrical shaped tool of copper material was selected. Whose diameter is 6mm. In this experiment, open channel type flushing has been used.

3.6 Flow chart of experiment



3.7 Process parameters of Die-sink EDM

There are many process parameters which can affect the response variable like surface roughness, micro hardness, tool wear rate, metal removal rate, surface topography, and surface integrity. These process parameters can be categorized based on the electrical property, type of material, mechanical properties of work-piece and tool, dielectric fluid`s properties and machine specifications.[24] For classification some scientific tool must be used for better understanding. There is one tool among seven quality tool known as Ishikawa fish bone diagram or Ishikawa`s cause and effect diagram which helps in categorizing the cause in major and minor categories so that anyone can understand the causes and sub causes for certain problem. Here MRR, SR, MH, TWR are the problem so it should be set at the head of fish bone diagram.



Selection of parameters is not a easy task but from previous research it is known that pulse on time, pulse off time, spark gap voltage and peak current are most effective parameters among others. Other parameters affect the response variable but not much. This can be verified with the help of 80-20 rule. According to 80-20 rule or Pareto chart, 80% effects (output) comes from 20% causes (input). It is also known as law of vital few. There are many process parameters other than pulse on time, pulse off time, spark gap voltage, peak current which can affect response (SR, MRR, TWR, MH) which are dielectric fluid pressure, flow rate of dielectric fluid, conductivity or resistance of dielectric fluid, tool shape, tool size, tool material, work-piece material etc. but these process parameters falls under 20 % causes. So priority should be given to those process parameters which are affecting response most.

3.7.1 Process parameters and their range for experimentation

Table 3.5 Process parameters and their range

S.N.	**Process parameter**	**Symbol**	**Range**	**Unit**
1	Pulse on time	T_{on}	500-1000	µs
2	Pulse off time	T_{off}	10-20	µs
3	Peak current	I	7-15	A
4	Spark gap voltage	V	90-150	V

3.9 Response Surface Methodology

This method was first developed by G. E. P. Box and K. B. Wilson in 1951. The main idea behind the response surface methodology is to get optimal response from series of designed experiment. Designing of experiment can done with the help of CCD, BBD etc. Originally, RSM was originated to model response characteristics (Box and Draper, 1987), and then drifted into the modelling of numerical experiments. But main difference is in the generated type of error by the response variables. In physical experiments, inaccuracy can be due, for example, to measurement errors while, In RSM, the errors are assumed to be random. RSM`s application is to reduce the overall cost of expensive analysis methods and their associated numerical noise [25].

Response surface methodology (RSM) is a composition of mathematical and statistical techniques for building the model. Ultimate objective of RSM is to optimize the response variable (Output parameters) by varying process parameter (Input parameters). Response variables are completely dependent on process parameters. Changes are made in input parameters, each change is known as run. And an experiments is a collection of runs. These changes are made in order to see response and reason behind response for each run. Response may be of maximum type or minimum type depending upon the response variable which is being considered. For example, we are doing machining operation on EDM and surface roughness and MRR are being considered as output variable or response variable, in that case SR must be minimum while MRR must be maximum for better machined surface and efficiency point of view.[2]

Lets assume y is the response variable while x_i are the input parameters and response variable is dependent on the input parameters

y = f ($x_1, x_2, x_3, \ldots, x_n$) …

Where

y = Response variable

$\mathbf{x_i}$ = i^{th} independent variable

Since quadratic equation is used in curve fitting so equation for response variable [Kwak, 2005; Gunaraj and Murugan, 1999]

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \qquad \textbf{………..….3.1}$$

Where

y = output response

xi = i^{th} control factor

β = regression coefficient

ε = random error

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.

3.9.1 Desirable features of RSM [3]

(a) Rotate-ability: Satisfactory distribution of information across the experimental region

(b) Minimum residual or error of prediction: Fitted values are as close as possible to observed value

(c) Good lack of fit detection

(d) Internal estimate of error

(e) Constant variance check

(f) Transformation can be detected

(g) Suitability for blocking

(h) Sequential construction of higher order design form simpler design

(i) Minimum number of treatment combinations

(j) Good graphical analysis through simple data patterns

(k) Good behavior when error in setting of input variable occurs

3.9 Box Behnken Design

Box Behnken design falls under response surface methodology and it was prepared by George E.P. Box and Donald Behnken in 1960 to get certain goals which are as following

(1) Each variable is assigned with three +1, 0, -1 which implies that in this method each variable must have three levels

(2) Design must fit a quadratic model that means in equation of response variable one independent variable must be squared one to make power of order two while interaction have power two too, so that's how response variable equation would be a quadratic equation.

(3) The ratio of no. of experimental points to the number of coefficient in quadratic model must lie between 1.5 to 2.6

(4) The estimation variance depend more or less only on the distance from the and should not fluctuate too much inside the smallest (hyper)cube containing the experimental points [27].

(a) Box Behnken design is nearly or fully rotatable but it contains region of poor prediction quality just like CCL.

(b) Its missing center may be useful when the experimenter should avoid combined factor extremes. This prevents possible loss of data in those cases. All BBD requires 3 level for each variable.[5]**.** These design requires fewer treatments than other designing method.

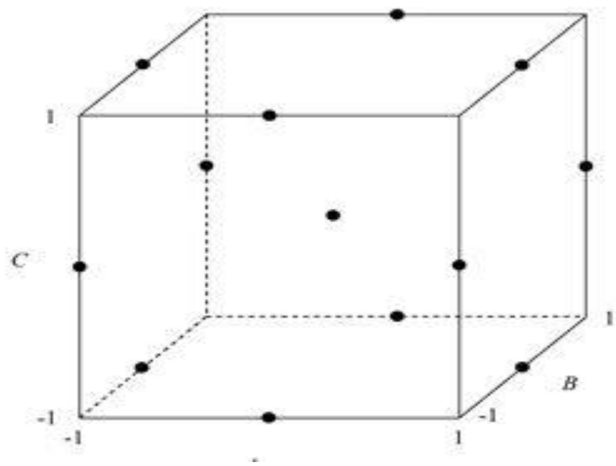
Table 3.6 Comparison between CCD and BBD

No. of factors	CCD	BBD
2	13	_
3	20	15
4	30	27
5	33	46
6	54	54

The Box-Behnken design is designing method under RSM which requires three levels for each process parameter to run experiment. It is a special 3-level design because it does not contain any points at the vertices in the cube. It has its own advantages when the points on the corners of the cube represent the combinations of level which are expensive or impossible to test because of physical process constraints.

Table 3.7 BBD for 3 factors at 3 level

Runs	Factors		
	A	B	C
1	-1	-1	0
2	-1	1	0
3	1	-1	0
4	1	1	0
5	-1	0	-1
6	-1	0	1
7	1	0	-1
8	1	0	1
9	0	-1	-1
10	0	-1	1
11	0	1	-1
12	0	1	1
13	0	0	0



(b)

Figure 3.5: Box-Behnken design for three factors

3.10 Conduct of Experiment

Experiments are conducted on Die Sink CNC machine whose model is Electronica Xpert-1. Each run is followed based on designing of experiment, done by BBD on Design of Experiment 6.08. In this study four parameters are variable to get response accordingly. A disc shape Ti-6Al-7Nb material as work-piece is used.

Steps which are followed for machining operation

(1) Preparation of work-piece means converting into disc of length 20mm from wire of 10mm diameter and 1meter length and making tool in cylindrical form whose diameter is of 6mm. **(2)** Work-piece is mounted on table and fixed in jigs and fixture situated on work table

(3) Cutting tool is installed vertically in head

(4) Tool head is moved from reference point to match the center of wok-piece w.r.t center of tool.

(5) Movement of tool head is manually controlled by operator.

(6) Programming is done for cutting operation and all variable and constant parameters are set according to the value of process parameters for each run based on design matrix.

3.11 Design matrix

Following table shows the design matrix of experimentation [28]

Table 3.8 Design matrix of Experiments

Std.	Run	Block	Factor 1 A: Peak current(A)	Factor 2 B: Pulse on time(μs)	Factor 3 C: Pulse off time(μs)	Factor 4 D: Spark gap voltage(V)
25	1	Block 1	11	750	15	120
15	2	Block 1	11	500	20	120
24	3	Block 1	11	1000	15	150
26	4	Block 1	11	750	15	120
27	5	Block 1	11	750	15	120
1	6	Block 1	7	500	15	120
14	7	Block 1	11	1000	10	120
9	8	Block 1	7	750	15	90
23	9	Block 1	11	500	15	150
11	10	Block 1	7	750	15	150
20	11	Block 1	15	750	20	120
8	12	Block 1	11	750	20	150
13	13	Block 1	11	500	10	120
19	14	Block 1	7	750	20	120
29	15	Block 1	11	750	15	120
21	16	Block 1	11	500	15	90
28	17	Block 1	11	750	15	120
3	18	Block 1	7	1000	15	120
4	19	Block 1	15	1000	15	120
2	20	Block 1	15	500	15	120
18	21	Block 1	15	750	10	120
7	22	Block 1	11	750	10	150
5	23	Block 1	11	750	10	90
12	24	Block 1	15	750	15	150
6	25	Block 1	11	750	20	90
22	26	Block 1	11	1000	15	90
17	27	Block 1	7	750	10	120
10	28	Block 1	15	750	15	90
16	29	Block 1	11	1000	20	120

3.12 Measurement of response variables [29]

In this study MRR, TWR, SR, MH are considered as response variable

3.12.1 Evaluation of MRR

Evaluation of MRR can be defined as ratio of difference in weight of material before and after machining to the time and density.

$$MRR = \frac{W_{wp_b} - W_{wp_a}}{t*\rho} \qquad \ldots\ldots\mathbf{3.2}$$

Where

$\mathbf{W_{wp_b}}$ – Weight of work-piece before machining

$\mathbf{W_{wp_a}}$ – Weight of work-piece after machining

t – Time for which machining is done

$\boldsymbol{\rho}$ – Density of material

3.12.2 Evaluation of TWR

Evaluation of TWR can be defined as ratio of difference in weight of material before and after machining to the time and density.

$$TWR = \frac{W_{t_b} - W_{t_a}}{t*\rho} \qquad \ldots\ldots\mathbf{3.3}$$

Where

$\mathbf{W_{t_b}}$ – Weight of tool before mach`ining

$\mathbf{W_{t_a}}$ – Weight of tool after machining

t – Time for which machining is done

$\boldsymbol{\rho}$ – Density of material

3.12.3 Measurement of surface roughness

Surface roughness is a measure of the surface texture. 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 EDMed 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 (Ra) is easy to define, as it measures and gives a general description of surface amplitude [30].

Fig 3.6 Surface Roughness (Ra) tester[Thapar University, Patiala]

Measurement of machined surface was done, after all the experimental runs were performed, by using surface roughness tester Mitutoyo surftestSJ-301 (series no.178)(contact type stylus based), having a display range of 0.01 to 100 μm as shown in Fig. The cut off length is 0.8 mm. Measurement of Ra was done at 3 places perpendicular to the direction of cut of the machined surface and mean of the three readings denoted average surface roughness.

3.12.4 Measurement of micro hardness

Hardness is not a physical property of a material, but a characteristic. Vicker Ltd. Developed Vicker hardness testing machine in 1921 by Robert L. Smith and George E. Sandland. It is easiest hardness testing machine among all because size of indenter is independent from calculation of hardness and testing is independent from type of materials. Its basic principle is based on resistance to plastic deformation of material with respect to standards. Unit is known as Vicker pyramid number (HV). Testing was done at 1000kg. And HV number is defined as

$$HV=\frac{F}{A}$$

Fig 3.7 Micro hardness tester [Thapar University, Patiala]

3.13 Design matrix and observation table

Table 3.9 Design matrix and observation table

Std.	Run	Block	Factor 1 A: Peak current(A)	Factor 2 B: Pulse on time (µs)	Factor 3 C: Pulse off time (µs)	Factor 4 D: Spark gap voltage (V)	Response 1 MRR (mg/min)	Response 2 TWR (mg/min)	Response 3 SR (µm)	Response 4 MH (HV)
25	1	Block 1	11	750	15	120	1.289	0.07846	2.489	1637.8
15	2	Block 1	11	500	20	120	1.2053	0.0672	2.14	1635.96
24	3	Block 1	11	1000	15	150	1.1537	0.0734	3.12	1572.98
26	4	Block 1	11	750	15	120	1.2472	0.07544	2.542	1632.49
27	5	Block 1	11	750	15	120	1.2413	0.0704	2.495	1639.3
1	6	Block 1	7	500	15	120	0.921	0.0372	1.136	1454.96
14	7	Block 1	11	1000	10	120	1.3921	0.0702	3.19	1574.45
9	8	Block 1	7	750	15	90	0.974	0.04084	1.65	1462.5075
23	9	Block 1	11	500	15	150	1.142	0.0754	2.31	1661.93
11	10	Block 1	7	750	15	150	0.81121	0.0372	1.581	1418.23
20	11	Block 1	15	750	20	120	1.4012	0.0984	3.18	1782.93
8	12	Block 1	11	750	20	150	1.162	0.0784	2.575	1618.23
13	13	Block 1	11	500	10	120	1.207	0.07872	2.24	1628.86
19	14	Block 1	7	750	20	120	0.9592	0.04672	1.58	1428.63
29	15	Block 1	11	750	15	120	1.274	0.0744	2.3	1637.8
21	16	Block 1	11	500	15	90	1.2637	0.06923	2.19	1626.34
28	17	Block 1	11	750	15	120	1.2749	0.0714	2.474	1652.569
3	18	Block 1	7	1000	15	120	0.9587	0.04172	2.153	1408.39
4	19	Block 1	15	1000	15	120	1.4749	0.116	3.82	1726.77
2	20	Block 1	15	500	15	120	1.4489	0.1188	3.48	1841.35
18	21	Block 1	15	750	10	120	1.4749	0.1288	3.721	1796.96
7	22	Block 1	11	750	10	150	1.1462	0.0774	2.63	1618.21
5	23	Block 1	11	750	10	90	1.4342	0.07232	2.374	1615.44
12	24	Block 1	15	750	15	150	1.4512	0.1372	3.912	1795.71
6	25	Block 1	11	750	20	90	1.2957	0.0644	2.39	1646.23
22	26	Block 1	11	1000	15	90	1.3477	0.0744	3.07	1589.48
17	27	Block 1	7	750	10	120	1.0124	0.0372	1.61	1452.34
10	28	Block 1	15	750	15	90	1.5145	0.12118	3.23	1802.38
16	29	Block 1	11	1000	20	120	1.2181	0.07072	3.02	1589.34

Chapter 4

Results and discussion

4.1 Introduction

This chapter is related to response variable and influence of process parameters on response variable. Experiments are conducted on Electronica Xpert-1 Die sinker type EDM machine. Every time, when experiment is conducted a set of process parameter combination is chosen which is designed by BBD on Design Expert-6.08. Results obtained are given in following table for each set of process parameter combination. MRR, TWR, SR, MH are considered as response variable. Obtained value of response variable are analyzed on Designed Expert 6.08 software and discussed in the following headings or sub headings.

4.2 Judgement of sufficiency of model fitting

Suitableness of model is investigated. Three different test (Sequential model sum of square(SMSOS), Lack of fit (LOF) and model summary statistics (MSS)) are conducted to check the sufficiency of model for MRR, TWR, SR, MH. Generally model with higher F value and lower p value is selected. Regression model show lack of fit when it fails to sufficiently describe the functional relationship between process parameters and response variable. Lack of fit exists if important term from model such interaction or quadratic terms are not included. If the p-value is less than or equal to α, you conclude that the model does not accurately fit the data.

4.3 ANOVA and mathematical model of response variables

Analysis of variance (ANOVA) is a statistical method which is used to 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 the sufficient precision which measures signal to noise ratio. Process variable whose p value is less than 0.05, that process variable is considered as significant for response variable. Here in this study backward elimination method with α= 0.05 is used which has very useful significant. It eliminates the insignificant term to adjust fitted quadratic model. Which process parameter affect the response variable most and accordingly finding the optimum solution for better efficiency is most important criteria [31].

Table 4.1 Results of response variables for different process parameters combination

Std.	Run	Block	Factor 1 A:Peak Current	Factor 2 B:Pulse On Time	Factor 3 C:Pulse Off Time	Factor 4 D:Spark Gap Voltage	Response 1 MRR (mg/min)	Response 2 TWR (mg/min)	Response 3 SR (µm)	Response 4 MH (HV)
25	1	Block 1	11	750	15	120	1.289	0.07846	2.489	1637.8
15	2	Block 1	11	500	20	120	1.2053	0.0672	2.14	1635.96
24	3	Block 1	11	1000	15	150	1.1537	0.0734	3.12	1572.98
26	4	Block 1	11	750	15	120	1.2472	0.07544	2.542	1632.49
27	5	Block 1	11	750	15	120	1.2413	0.0704	2.495	1639.3
1	6	Block 1	7	500	15	120	0.921	0.0372	1.136	1454.96
14	7	Block 1	11	1000	10	120	1.3921	0.0702	3.19	1574.45
9	8	Block 1	7	750	15	90	0.974	0.04084	1.65	1462.508
23	9	Block 1	11	500	15	150	1.142	0.0754	2.31	1661.93
11	10	Block 1	7	750	15	150	0.81121	0.0372	1.581	1418.23
20	11	Block 1	15	750	20	120	1.4012	0.0984	3.18	1782.93
8	12	Block 1	11	750	20	150	1.162	0.0784	2.575	1618.23
13	13	Block 1	11	500	10	120	1.207	0.07872	2.24	1628.86
19	14	Block 1	7	750	20	120	0.9592	0.04672	1.58	1428.63
29	15	Block 1	11	750	15	120	1.274	0.0744	2.3	1637.8
21	16	Block 1	11	500	15	90	1.2637	0.06923	2.19	1626.34
28	17	Block 1	11	750	15	120	1.2749	0.0714	2.474	1652.569
3	18	Block 1	7	1000	15	120	0.9587	0.04172	2.153	1408.39
4	19	Block 1	15	1000	15	120	1.4749	0.116	3.82	1726.77
2	20	Block 1	15	500	15	120	1.4489	0.1188	3.48	1841.35
18	21	Block 1	15	750	10	120	1.4749	0.1288	3.721	1796.96
7	22	Block 1	11	750	10	150	1.1462	0.0774	2.63	1618.21
5	23	Block 1	11	750	10	90	1.4342	0.07232	2.374	1615.44
12	24	Block 1	15	750	15	150	1.4512	0.1372	3.912	1795.71

6	25	Block 1	11	750	20	90	1.2957	0.0644	2.39	1646.23
22	26	Block 1	11	1000	15	90	1.3477	0.0744	3.07	1589.48
17	27	Block 1	7	750	10	120	1.0124	0.0372	1.61	1452.34
10	28	Block 1	15	750	15	90	1.5145	0.12118	3.23	1802.38
16	29	Block 1	11	1000	20	120	1.2181	0.07072	3.02	1589.34

Results and analysis formed and analyzed by the application of ANOVA test for samples are discussed in the following section

4.3.1 Adequacy checking of model For Ti-6Al-7Nb samples

Table 4.2 Adequacy checking of model for MRR

(a) Sequential Model Sum of Squares

Source	Sum Of Squares	DF	Mean Square	F Value	Prob > F	Remark
Mean	43.9386	1	43.9386			
Linear	0.9190	4	0.2297	91.3877	< 0.0001	
2FI	0.0173	6	0.0029	1.20542	0.3481	
Quadratic	0.0237	4	0.0059	4.2807	0.0181	Suggested
Cubic	0.0172	8	0.0022	5.9876	0.0213	Aliased
Residual	0.0022	6	0.00036			
Total	44.9179	29	1.5489			

(b) Lack of Fit Tests

Source	Sum Of Squares	DF	Mean Square	F Value	Prob > F	Remark
Linear	0.0587	20	0.0029	7.1890	0.0343	
2FI	0.0414	14	0.00296	7.2444	0.0346	
Quadratic	0.0177	10	0.0018	4.3424	0.0849	Suggested
Cubic	0.00052	2	0.00026	0.6394	0.5742	Aliased
Pure Error	0.0016	4	0.00041			

(c) Model Summary Statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	Remark
Linear	0.0501	0.9384	0.9281	0.9073	0.0908	
2FI	0.0489	0.9561	0.9316	0.8714	0.126	
Quadratic	0.0372	0.9802	0.9605	0.8931	0.1047	Suggested
Cubic	0.01895	0.9978	0.98973	0.92063	0.0777	Aliased

Table 4.3 Adequacy checking of model for TWR

(a) Sequential Model Sum of Squares

Source	Sum Of Squares	DF	Mean Square	F Value	Prob > F	Remark
Mean	0.1674	1	0.1674			
Linear	0.0194	4	0.00485	88.5102	< 0.0001	
2FI	0.00058	6	9.62E-05	2.3488	0.0749	
Quadratic	0.00043	4	0.00011	4.8971	0.0111	Suggested
Cubic	0.00024	8	2.96E-05	2.5248	0.1377	Aliased
Residual	7.04E-05	6	1.17E-05			
Total	0.188087	29	0.006486			

(b) Lack of Fit Tests

Source	Sum Of Squares	DF	Mean Square	F Value	Prob > F	Remark
Linear	0.00127	20	6.37E-05	6.0850	0.0460	
2FI	0.00069	14	4.97E-05	4.7502	0.0717	
Quadratic	0.000266	10	2.66E-05	2.5386	0.1914	Suggested
Cubic	2.86E-05	2	1.43E-05	1.3650	0.3533	Aliased
Pure Error	4.18E-05	4	1.05E-05			

(c) Model Summary Statistics

Source	Std Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	Remark
Linear	0.0074	0.9365	0.9259	0.90120	0.00203	
2FI	0.0064	0.9644	0.9446	0.8884	0.0023	
Quadratic	0.00469	0.9852	0.9703	0.9230	0.0016	Suggested
Cubic	0.00343	0.9966	0.9841	0.7983	0.00418	Aliased

Table 4.4 Adequacy checking of model for Surface Roughness

(a) Sequential Model Sum of Squares

Source	Sum Of Squares	DF	Mean Square	F Value	Prob > F	Remark
Mean	191.912	1	191.912			
Linear	13.4487	4	3.3622	124.837	< 0.0001	
2FI	0.3246	6	0.0541	3.0258	0.0317	
Quadratic	0.1752	4	0.0438	4.1841	0.0196	Suggested
Cubic	0.1017	8	0.0127	1.6999	0.2671	Aliased
Residual	0.0449	6	0.0075			
Total	206.007	29	7.1037			

(b) Lack of Fit Tests

Source	Sum Of Squares	DF	Mean Square	F Value	Prob > F	Remark
Linear	0.6118	20	0.0306	3.5378	0.1143	
2FI	0.2872	14	0.0205	2.3727	0.2094	
Quadratic	0.112	10	0.0112	1.2952	0.4324	Suggested
Cubic	0.0102	2	0.00514	0.5948	0.5941	Aliased
Pure Error	0.03459	4	0.008647			

(c) Model Summary Statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	Remark
Linear	0.1641	0.9541	0.9465	0.9316	0.9645	
2FI	0.1337	0.9772	0.9645	0.9398	0.8484	
Quadratic	0.1023	0.9896	0.9792	0.9504	0.6991	Suggested
Cubic	0.0865	0.9968	0.9851	0.8911	1.5353	Aliased

Table 4.5 Adequacy checking of model for Micro Hardness

(a) Sequential Model Sum of Square

Source	Sum Of Squares	DF	Mean Square	Value	Prob > F	Remark
Mean	76005789.5	1	76005789.5			
Linear	387736.943	4	96934.2357	286.7422	< 0.0001	
2FI	2463.55791	6	410.592986	1.3082	0.3035	
Quadratic	3566.78499	4	891.696246	5.9933	0.0050	Suggested

Cubic	1823.76239	8	227.970299	5.2775	0.0288	Aliased
Residual	259.181761	6	43.1969601			
Total	76401639.8	29	2634539.3			

(b) Lack of Fit Tests

Source	Sum Of Squares	DF	Mean Square	Value	Prob > F	Remark
Linear	7888.74	20	394.44	7.03	0.0357	
2FI	5425.18	14	387.51	6.9	0.0377	
Quadratic	1858.39	10	185.84	3.31	0.1299	Suggested
Cubic	34.63	2	17.32	0.31	0.7506	Aliased
Pure Error	224.55	4	56.14			

(c) Model Summary Statistics

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	Remark
Linear	18.39	0.9795	0.9761	0.9709	11504.7	
2FI	17.72	0.9857	0.9778	0.9665	13260.3	
Quadratic	12.2	0.9947	0.9895	0.9721	11055.2	Suggested
Cubic	6.57	0.9993	0.9969	0.9865	5337.9	Aliased

4.3.2 ANOVA and mathematical model for MRR

Design Expert 6.08® suggested quadratic model for MRR. ANOVA for quadratic model at 95% confidence level shown in table 4.6. Estimated F value for model is 103.32 and p value is under 0.0001, which implies that there is only 0.01% probability that a "Model F value" could occur because of noise or effect of unknown parameter. ANOVA for quadratic model is designed at 95% confidence level which means 5% (Prob. > 0.005) is the level for which rejection would occur that can be because of noise (common error) or because of special cause.

Significant term: Confidence level is greater than 95%, which implies Probability is greater than F value. Then it can be concluded that model term or that process parameter/interaction of process parameter is significant. In other work we can say that if value of "Prob.>F" for any model term is less than 0.05, that model term is significant model term.

Significant term: Confidence level is lesser than 95%, which implies Probability is lesser than F value. Then it can be concluded that model term or that process parameter/interaction of process parameter is insignificant or not significant. In other work we can say that if value of "Prob.<F" for any model term is less than 0.05, that model term is insignificant model term.

Here, the value of F for lack of fit is 3.5 which is below 5 which implies that "Lack of fit" is not significant with respect to pure error. Obtained probability for lack of fit is 0.1049 or 10.49% which is above 0.05 or 5% that implies lack of fit is ingnificant. Non significant lack of fit is good.

R^2: Another term is R square. It's a statistical measuring term in regression analysis which measure that how well data fits the regression model. It is also known or called as "coefficient of determination". It's a ratio of % of response variable variation to total.

$$R^2 = \frac{\%\ of\ Response\ variable\ variation}{Total\ variaion} = \frac{SS_{model}}{SS_{model}+SS_{residual}} = \frac{SS_{model}}{SS_{total}} \quad \text{....4.1}$$

Adjusted R^2: Adjusted R^2 is a measure of the amount of variation around the mean explained by the model, adjusted for the number of terms in the model. The adjusted R-squared decreases as the number of terms in the model [32]

$$R^2_{adj} = 1- \frac{SS_{residual}/DF_{residual}}{(SS_{model}+SS_{residual})*(DF_{model}+DF_{residual})} \quad \text{.........4.2}$$

Where
SS- Sum of square
DF- Degree of freedom

Predicted R^2: It is a measure of the amount of variation in **new data** explained by the model.

$$R^2_{pred} = 1- \frac{PRESS}{SS_{total}-SS_{block}} \quad \ldots\ldots\ldots\ldots 4.3$$

Adequate Precision: Basically a measure of S/N (signal to noise ratio), It gives you a factor by which you can judge your model to see if it "adequate" to navigate through the design space and be able to predict the response. And its desired values must be greater than 4.0(>4).
It can be calculated by following equation [33]

$$\text{Adequate Precision} = \frac{\text{Maximum predicted response} - \text{Minimum predicted response}}{\text{Avg. Std. deviation of all predicted response}} \quad \ldots.4.4$$

Here in this study value of R^2 is 0.9718 which quite close to 1, means response data is quite around the mean. And R^2_{pred} (0.943) value is close to the R^2_{adj} (0.9624). So it means they are in agreement. "Adequate Precision" measures the signal to noise ratio. And ratio of signal to noise greater than 4 is desirable. And in study ratio value 35.8 is obtained. Which shows signal is sufficient.

Table 4.6 ANOVA for response surface of reduced quadratic model for MRR

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	Remark	% Contribution
Model	0.9517	7	0.136	103.318296	< 0.0001	Significant	
A	0.8159	1	0.8159	620.049921	< 0.0001	Significant	42.009
B	0.01064	1	0.01064	8.08456356	0.0097	Significant	0.5478
C	0.01507	1	0.01507	11.4546365	0.0028	Significant	0.7823
D	0.0774	1	0.0774	58.7874971	< 0.0001	Significant	3.983
A2	0.01933	1	0.01933	14.6882335	0.0010	Significant	0.996
BC	0.00742	1	0.0074	5.64004225	0.0272	Significant	0.38211
CD	0.00595	1	0.00595	4.52317774	0.0455	Significant	0.2876
Residual	0.02764	21	0.00132				
Lack of Fit	0.02601	17	0.00153	3.74608036	0.1049	Not Significant	0.254
Pure Error	0.00163	4	0.00041				
Cor Total	0.9793	28					

Std. Dev.	0.0363	**R-Squared**	0.9718
Mean	1.2309	**Adj R-Squared**	0.962
C.V.	2.9471	**Pred R-Squared**	0.9431
PRESS	0.0557	**Adeq Precision**	35.8

Legend: A- Peak current, B- Pulse on time, C- Pulse off time, D- Spark gap voltage

The mathematical relationship for the MRR correlated to the considered process variables is obtained as follows:

$$MRR = 0.553 + 0.137 * \text{ Peak current } + 6.36E - 04 * \text{ Pulse on time } - 0.0121 * \text{ Pulse off time} - 6.534E - 03 * \text{Spark gap voltage} - 3.27614E - 03 * \text{ Peak current}^2 - 3.446E - 05 * \text{ Pulse on time } * \text{ Pulse off time} + 2.572E - 04 * \text{ Pulse off time } * \text{Spark gap voltage}$$

Design-Expert Plot For MRR

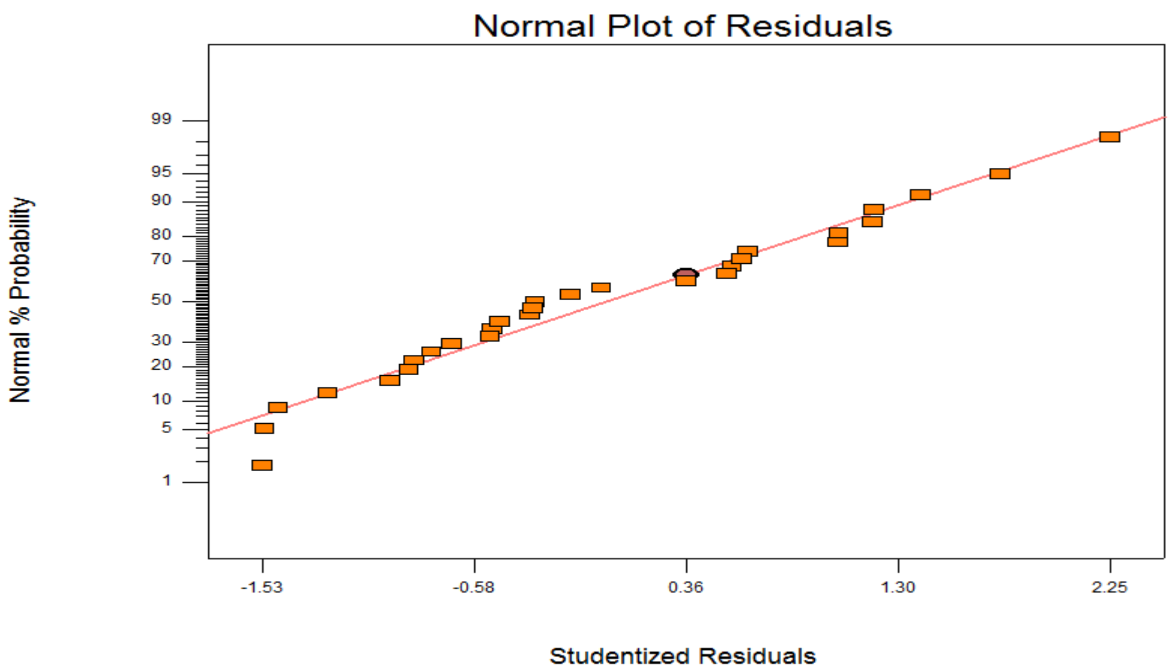


Figure 4.1 Normal probability plots of residuals for MRR

Design-Expert Plot For MRR

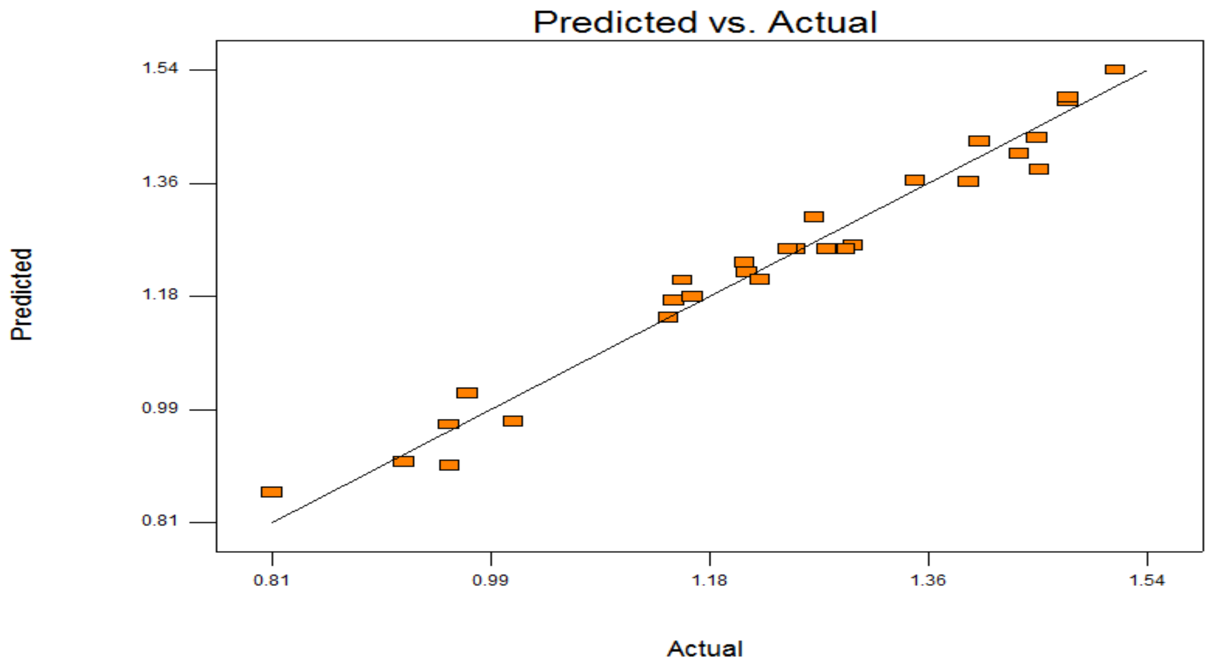


Figure 4.2 Plot of actual versus predicted for MRR

4.3.3 ANOVA and mathematical model for TWR

Design Expert 6.08® suggested quadratic model for TWR. ANOVA for quadratic model at 95% confidence level shown in table 4.7. Estimated F value for model is 157.92 and p value is under 0.0001, which implies that there is only 0.01% probability that a "Model F value" could occur because of noise or effect of unknown parameter. ANOVA for quadratic model is designed at 95% confidence level. Here, the value of F for lack of fit is 2.27 which is below 5 which implies that "Lack of fit" is not significant with respect to pure error. Obtained probability for lack of fit is 0.2218 or 22.18% which is greater than 0.05 or 5% which implies Lack of fit is insignificant.

Moreover, R^2 value is 0.9773, which confirms that accuracy and general ability of polynomial model is good. Further, predicted R2 of 0.9339 is in reasonable agreement with adjusted R^2 of 0.9711 and it indicates a high correlation between observed values and predicted values.

Figure 4.3 shows normal probability plot of residuals for TWR. 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 4.4 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 43.982 and it suggests that quadratic model can be used to navigate in the design space.

The mathematical relationship for the TWR correlated to the considered process variables is obtained as follows The mathematical relationship for the TWR correlated to the considered process variables is obtained as follows

$$\begin{aligned} \text{TWR} = {} & -0.0143 + 2.862\text{E} - 03 * \text{ Peak current} + 4.842\text{E} - 03 * \text{ Peak current} + 4.842 \\ & - 03 * \text{Pulse off time} - 3.488\text{E} - 04 * \text{ Spark gap voltage} + 4.41\text{E} - 04 \\ & * \text{ Peak current}^2 - 4.99\text{E} - 04 * \text{ Peak current } * \text{ Pulse off time} + 4.096\text{E} \\ & - 05 * \text{Peak current} * \text{Spark gap voltage} \end{aligned}$$

Table 4.7 ANOVA for response surface of reduced quadratic model for TWR

Source	Sum Of Squares	DF	Mean Square	F Value	Prob > F	Remark	% Contribution
Model	0.02	6	3.37E-03	157.92	< 0.0001	significant	
A	0.019	1	0.019	896.86	< 0.0001	significant	42.009
C	1.26E-04	1	1.26E-04	5.87	0.0241	significant	0.5478
D	1.12E-04	1	1.12E-04	5.23	0.0321	significant	0.7823
A2	3.50E-04	1	3.50E-04	16.38	0.0005	significant	3.983
AC	3.98E-04	1	3.98E-04	18.65	0.0003	significant	0.996
AD	9.66E-05	1	9.66E-05	4.52	0.0449	significant	0.38211
Residual	4.70E-04	22	2.14E-05				0.2876
Lack of Fit	4.28E-04	18	2.38E-05	2.27	0.2218	not significant	
Pure Error	4.18E-05	4	1.05E-05				0.254
Cor Total	0.021	28					

Std. Dev.	0.0046	**R-Squared**	0.9773
Mean	0.076	**Adj. R-Squared**	0.9711
C.V.	6.084	**Pred. R-Squared**	0.9339
PRESS	0.0014	**Adeq. Precision**	43.9824
Legend: A- Peak current, B- Pulse on time, C- Pulse off time, D- Spark gap voltage			

Design-Expert Plot For TWR

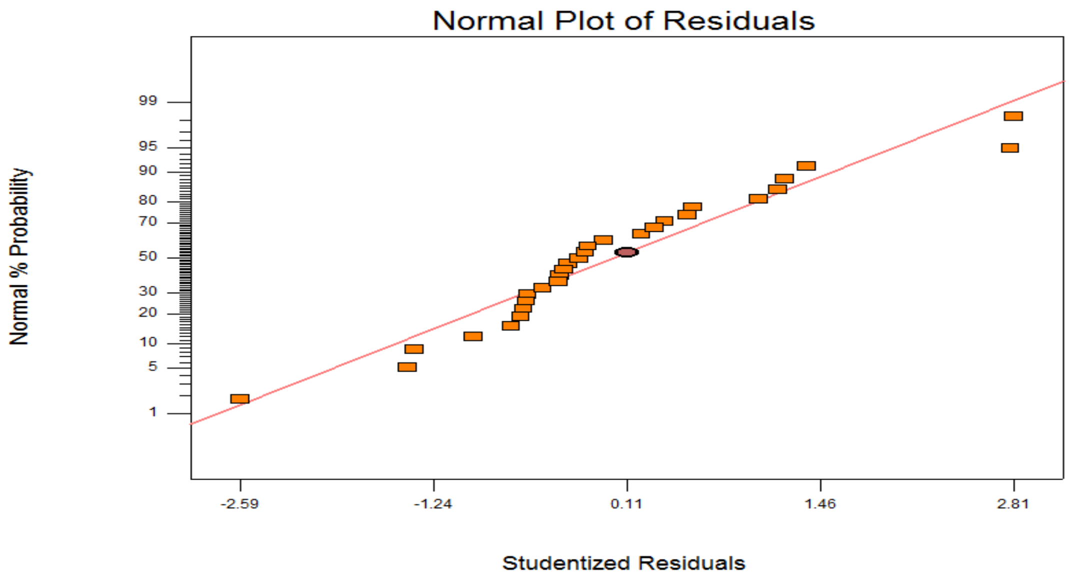


Figure 4.3 Normal probability plots of residuals for TWR

Design-Expert Plot For TWR

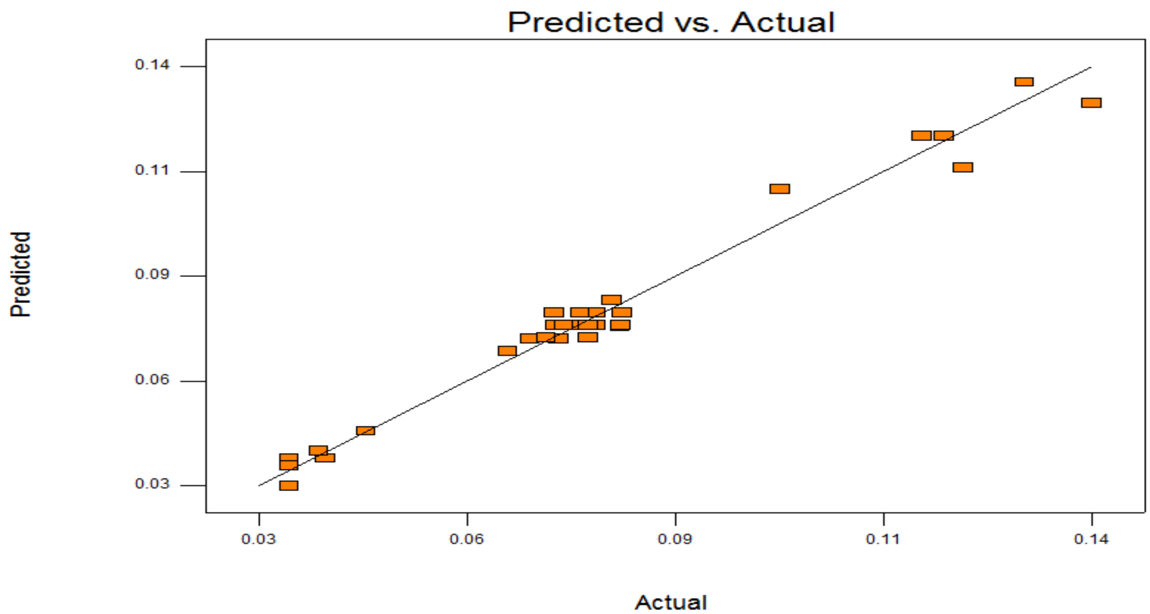


Figure 4.4 Plot of actual versus predicted for TWR

4.3.4 ANOVA and mathematical model for SR

Estimated F value for model is 189.44 and p value is under 0.0001, which implies that there is only 0.01% probability that a "Model F value" could occur because of noise or effect of unknown parameter. ANOVA for quadratic model is designed at 95% confidence level. Here, the value of F for lack of fit is 1.08 which is below 5 which implies that "Lack of fit" is not significant with respect to pure error. Obtained probability for lack of fit is 0.528 or 52.8% which is greater than 0.005 or 5% which implies Lack of fit is insignificant.

Moreover, R^2 value is 0.987, which confirms that accuracy and general ability of polynomial model is good. Further, predicted R2 of 0.9674 is in reasonable agreement with adjusted R^2 of 0.9818 and it indicates a high correlation between observed values and predicted values.

Figure 4.5 shows normal probability plot of residuals for SR. 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 4.6 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 51.55 and it suggests that quadratic model can be used to navigate in the design space.

The mathematical relationship for the SR correlated to the considered process variables is obtained as follows

$$\text{SR} = -0.666 + 0.277 * \text{Peak current} + 7.836\text{E} - 05 * \text{Pulse on time} + 0.0556 * \text{Pulse off time} - 0.014 * \text{SPARK GAP VOLTAGE} + 0.044 * \text{Peak current2} + 1.089\text{E} - 05 * \text{Pulse on time2} + 2.273\text{E} - 06 * \text{Pulse off time2} - 1.693\text{E} - 04 * \text{Peak current} * \text{Pulse on time} - 6.387\text{E} - 03 * \text{Peak current} * \text{Pulse off time} + 1.565\text{E} - 03 * \text{Peak current} * \text{Spark gap voltage}$$

Table 4.8 ANOVA for response surface of reduced quadratic model for SR

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	Remark
Model	13.91	8	1.74	189.44	< 0.0001	significant
A	11.28	1	11.28	1228.55	< 0.0001	Significant
B	1.98	1	1.98	215.93	< 0.0001	Significant
C	0.065	1	0.065	7.03	0.0153	Significant
D	0.12	1	0.12	13.6	0.0015	Significant
B2	0.14	1	0.14	15.46	0.0008	Significant
AB	0.11	1	0.11	12.48	0.0021	Significant
AC	0.065	1	0.065	7.11	0.0148	Significant
AD	0.14	1	0.14	15.36	0.0008	significant
Residual	0.18	20	9.18E-03			
Lack of Fit	0.15	16	9.31E-03	1.08	0.528	not significant
Pure Error	0.035	4	8.65E-03			
Cor Total	14.1	28				
Model	13.91	8	1.74	189.44	< 0.0001	significant

Std. Dev.	0.096	**R-Squared**	0.987
Mean	2.57	**Adj. R-Squared**	0.9818
C.V.	3.72	**Pred. R-Squared**	0.9674
PRESS	0.46	**Adeq. Precision**	51.555
Legend: A- Peak current, B- Pulse on time, C- Pulse off time, D- Spark gap voltage			

Design-Expert Plot For SR

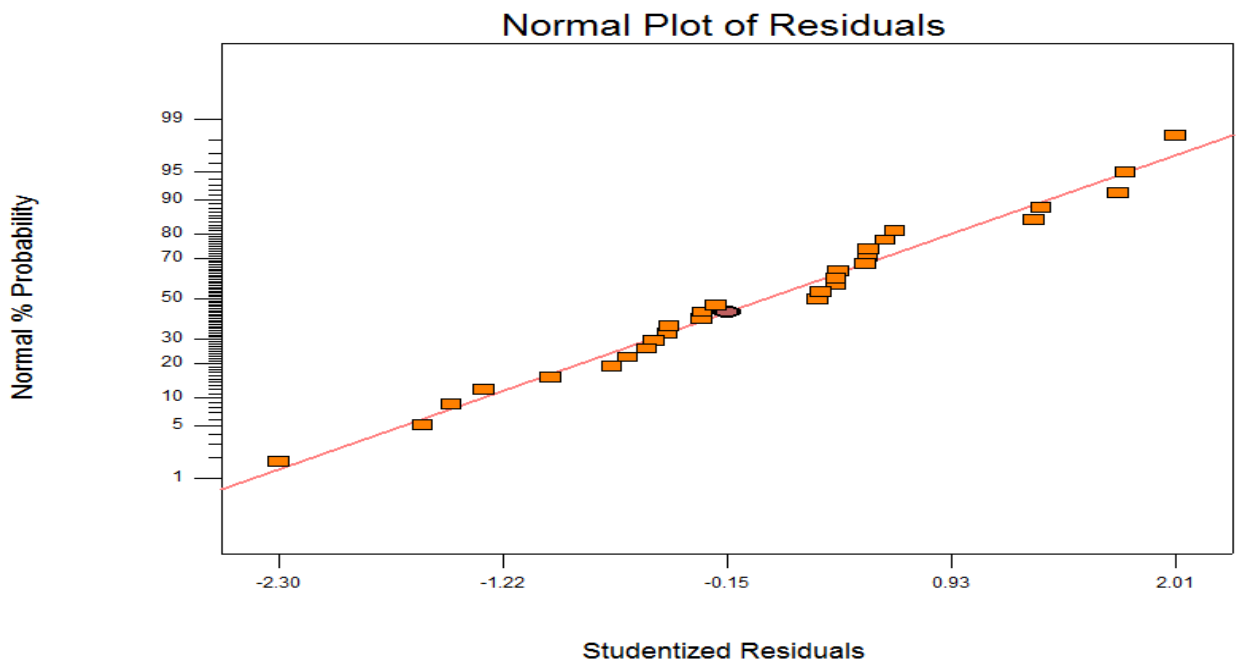


Figure 4.5 Normal probability plots of residuals for SR

Design-Expert Plot For SR

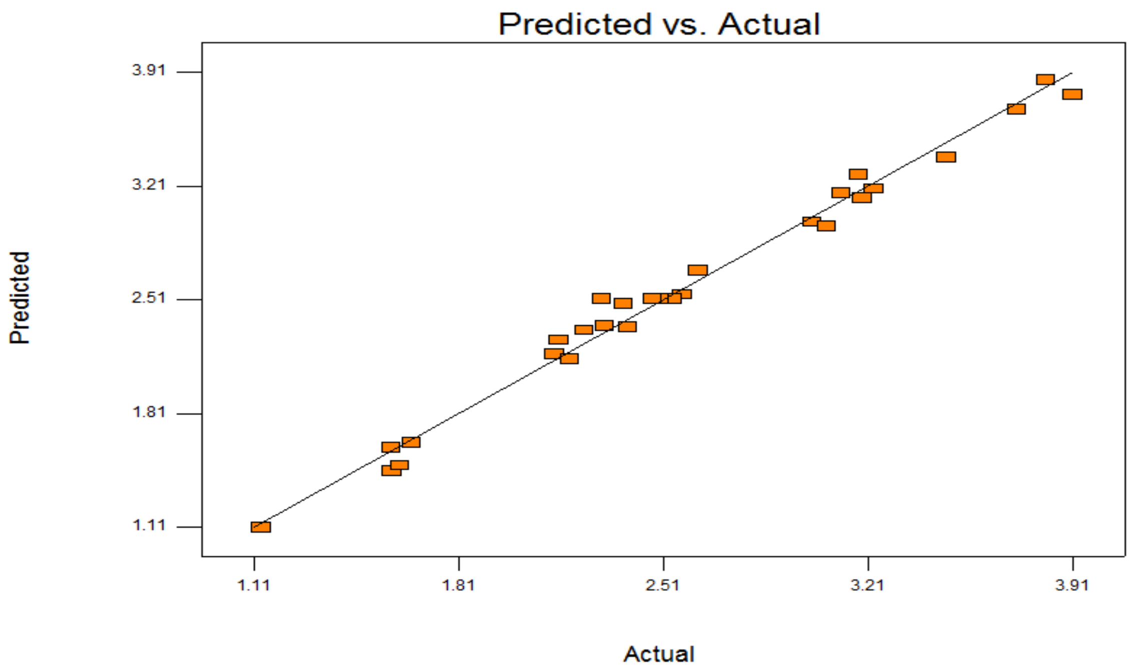


Figure 4.6 Plot of actual versus predicted for SR

4.3.5 ANOVA and mathematical model for MH

Estimated F value for model is 439.7334 and p value is under 0.0001, which implies that there is only 0.01% probability that a "Model F value" could occur because of noise or effect of unknown parameter. ANOVA for quadratic model is designed at 95% confidence level. Here, the value of F for lack of fit is 4.54597 which is below 5 which implies that "Lack of fit" is not significant with respect to pure error. Obtained probability for lack of fit is 0.0759 or 7.59% which is greater than 0.005 or 5% which implies Lack of fit is insignificant.

Moreover, R^2 value is 0.9865, which confirms that accuracy and general ability of polynomial model is good. Further, predicted R2 of 0.9808 is in reasonable agreement with adjusted R^2 of 0.9843 and it indicates a high correlation between observed values and predicted values.

Figure 4.7 shows normal probability plot of residuals for MH. 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 4.8 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 67.588 and it suggests that quadratic model can be used to navigate in the design space.

The mathematical relationship for the MH correlated to the considered process variables is obtained as follows

$$\mathrm{MH} = 947.7591 + 56.9403 * \text{Peak current} - 2.6426\mathrm{E} - 04 * \text{Pulse on time2} - 0.017 * \text{Peak current} * \text{Pulse on time}$$

Table 4.9 ANOVA for response surface of reduced quadratic model for MH

Source	Sum Of Squares	DF	Mean Square	F Value	Prob > F	Remark
Model	390521.7	4	97630.43	439.7334	< 0.0001	significant
A	374901.8	1	374901.8	1688.58	< 0.0001	significant
B	12544.69	1	12544.69	56.50203	< 0.0001	significant
B2	1918.904	1	1918.904	8.64286	0.0072	significant
AB	1156.34	1	1156.34	5.208226	0.0316	significant
Residual	5328.525	24	222.0219			
Lack of Fit	5103.976	20	255.1988	4.545969	0.0759	not significant
Pure Error	224.5495	4	56.13738			
Cor Total	395850.2	28				

Std. Dev.	14.9	**R-Squared**	0.9865
Mean	1618.92	**Adj R-Squared**	0.9843
C.V.	0.92	**Pred R-Squared**	0.9808
PRESS	7595.82	**Adeq Precision**	67.588
Legend: A- Peak current, B- Pulse on time, C- Pulse off time, D- Spark gap voltage			

Design-Expert Plot For MH

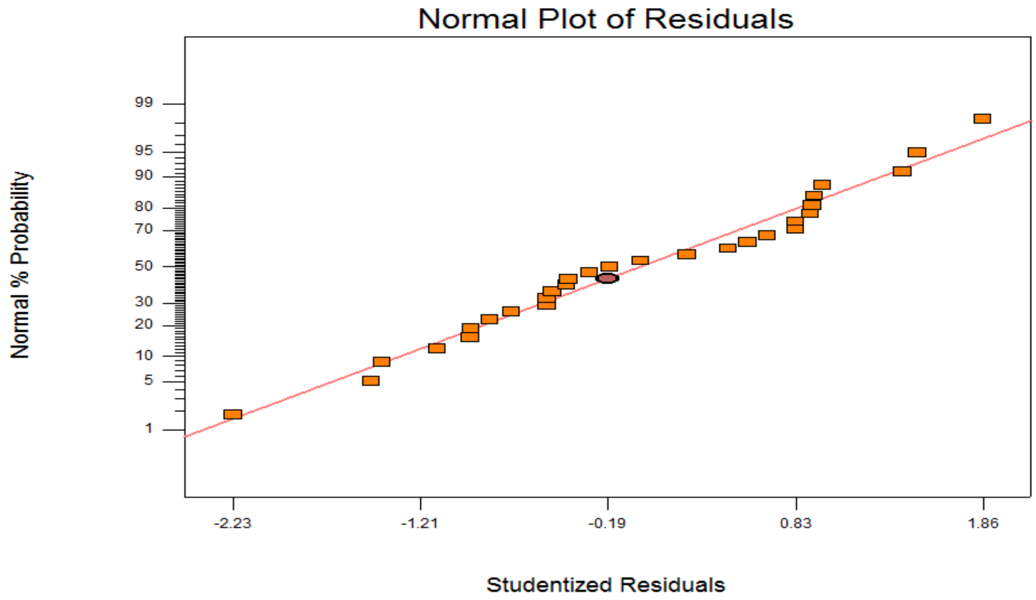


Figure 4.7 Normal probability plots of residuals for MH

Design-Expert Plot For MH

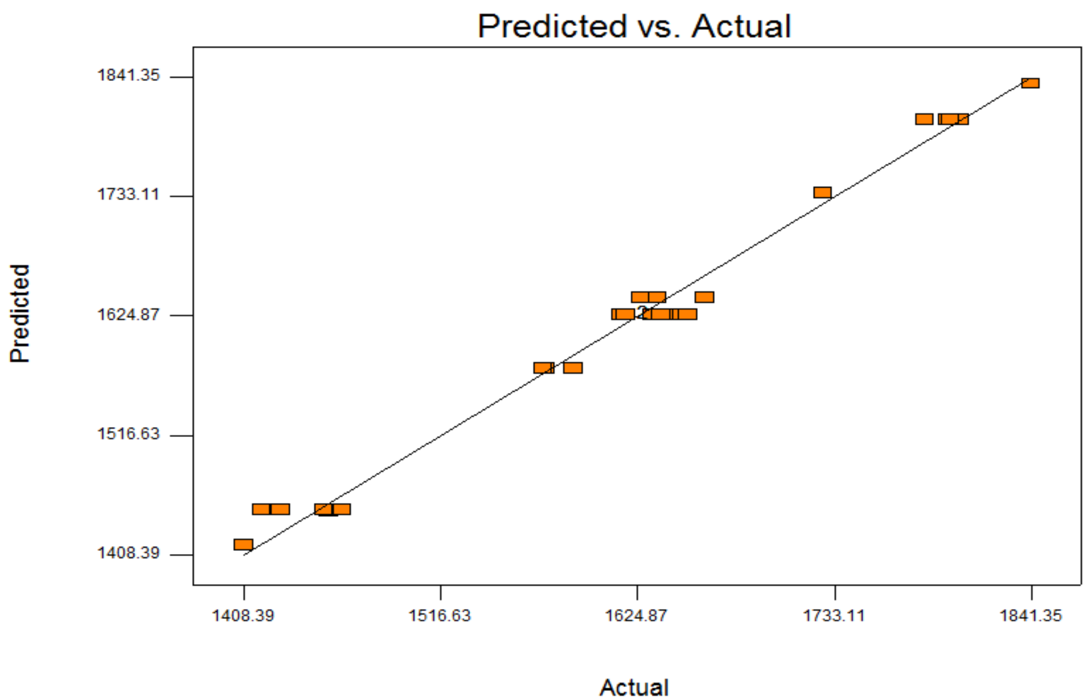


Figure 4.8 Plot of actual versus predicted for MH

4.4 Effect Of Process Parameter On Response Characteristics

This part represents the impact of process parameters on response characteristics (MRR, TWR, SR, MH). It studies individual and in addition the interaction effect on different response characteristics.

4.4.1 Effect Of Process Parameters On MRR

Plots for effect of process parameter as individual and as well as interaction of one to other on MRR are shown in fig from 4.9 to 5.5. MRR was affected by mainly Peak current(I_p), Pulse on time(T_{ON}), Pulse off time(T_{OFF}), Spark gap voltage (V). MRR is increased from 0.81121to 1.5145 mg/min as peak current was increased from 7 to 15 A. Higher peak current and pulse on time as input parameter means higher applied energy results in higher MRR While as pulse off time is increased MRR was decreased, it`s because, enlarging the length of time span for pulse off decrease the number of sparks between the gap of tool and work-piece. As studied in previous papers[Md. Ashikur Rahman Khan, 2015]. Since pulse on time and pulse off time demonstrated the higher percentage contribution when contrasted with the other two factors, they can be viewed as most significant to the MRR.

Two interactions have been found to be considerable $T_{on} \times T_{off}$ and $T_{off} \times SV$ as shown in Figures from 4.9 to 4.15. Optimum response can be attained when the parameters are set at; I_p=11A, T_{on}= 750 mu, T_{off} = 15 mu, SV= 120V.

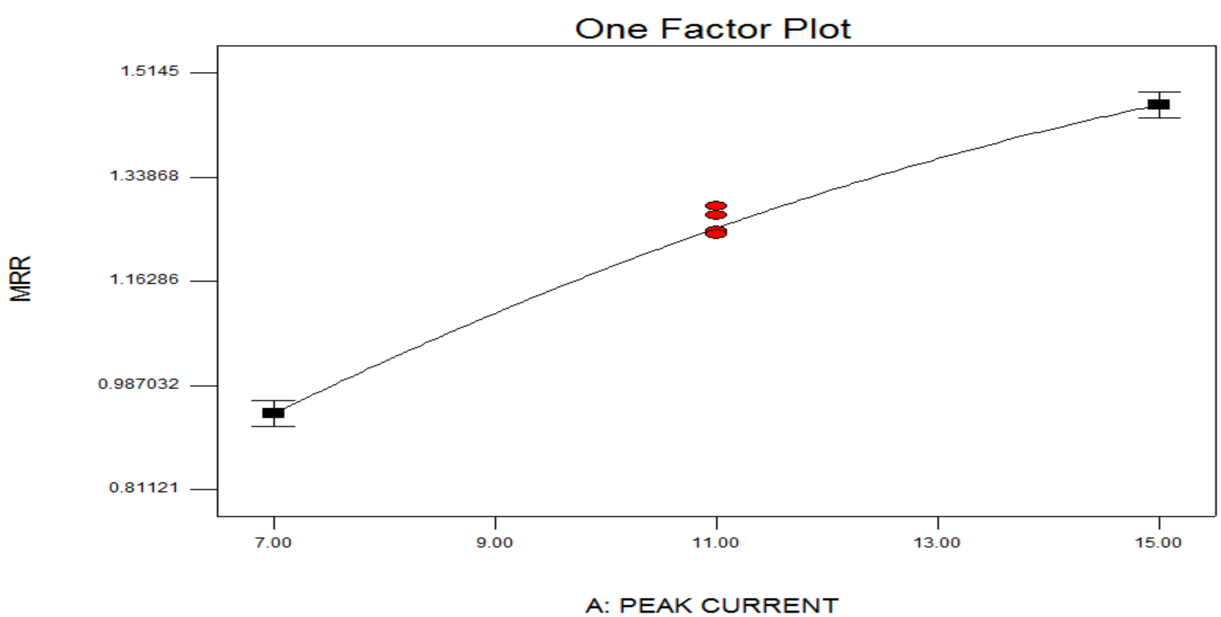


Figure 4.9 Effect of peak current on MRR

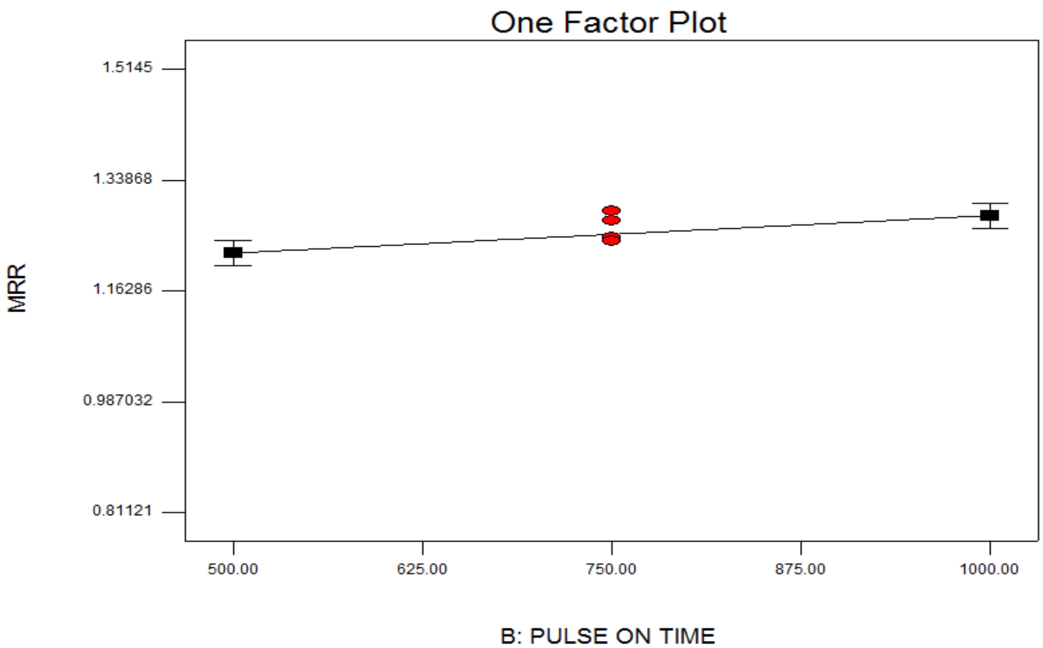


Figure 4.10 Effect of pulse on time on MRR

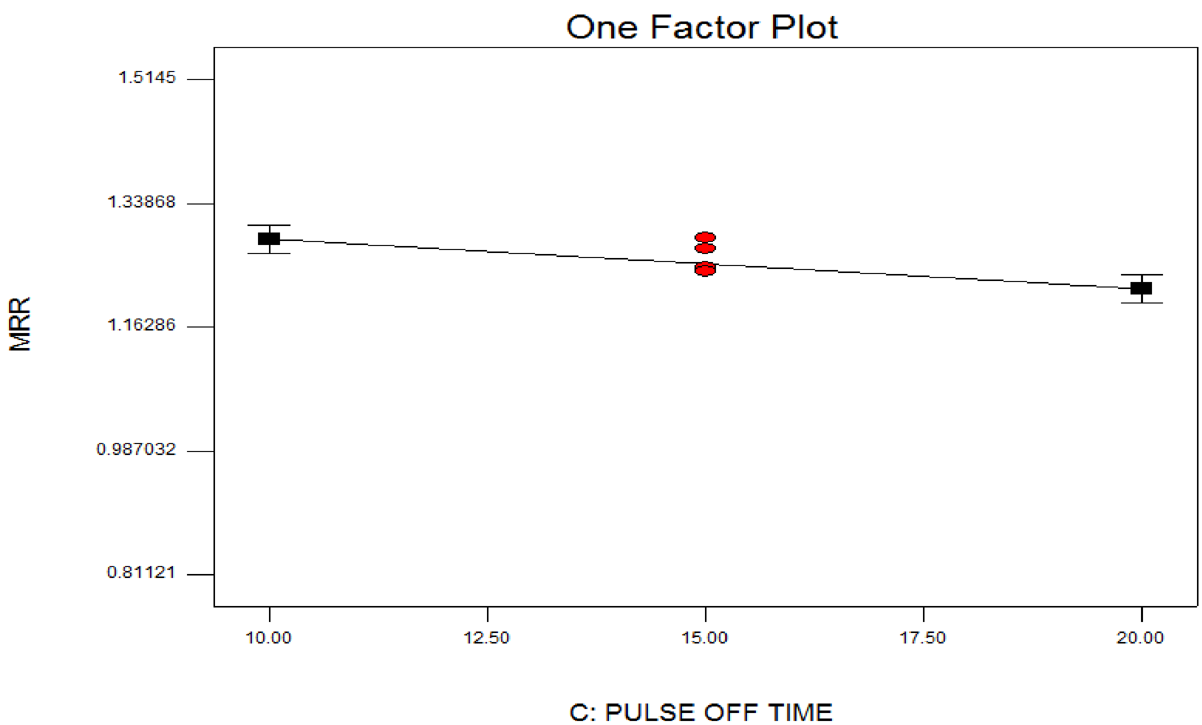


Figure 4.11 Effect of pulse off time on MRR

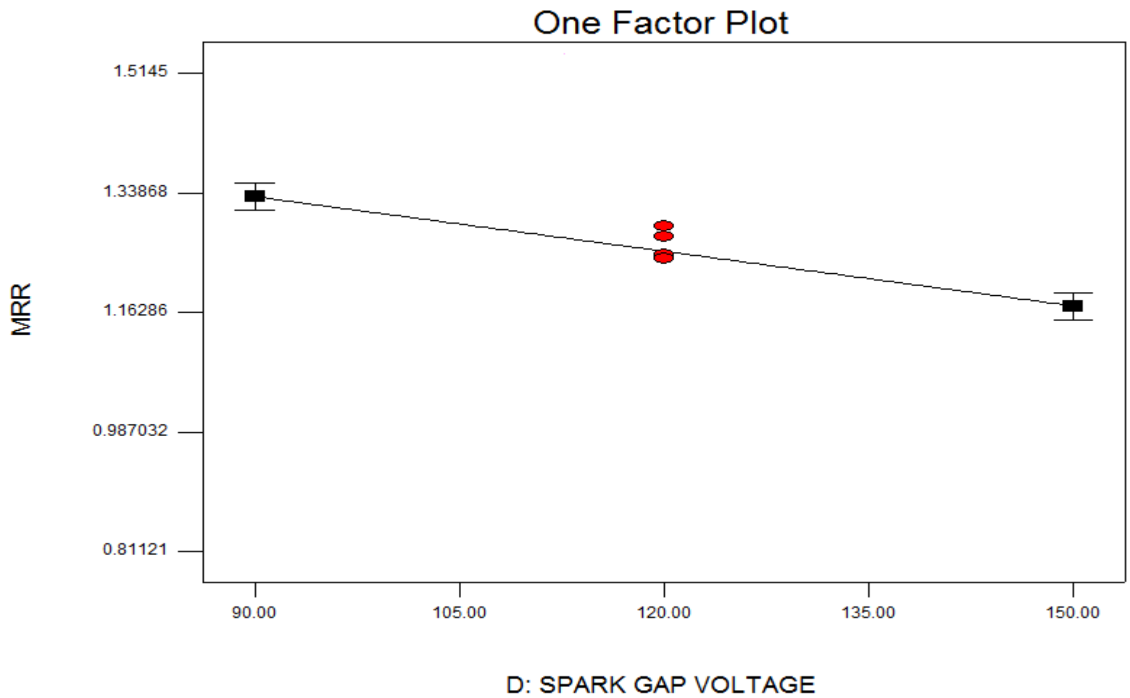


Figure 4.12 Effect of Spark gap voltage on MRR

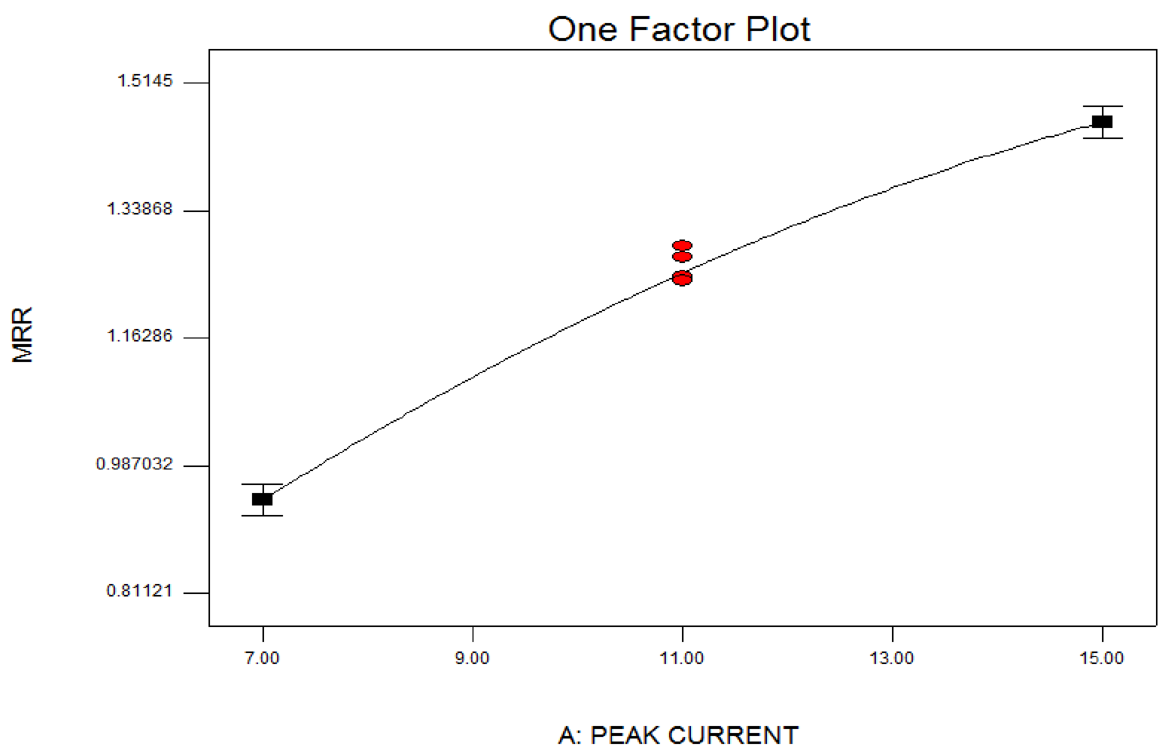


Figure 4.13 Effect of peak current^2 voltage on MRR

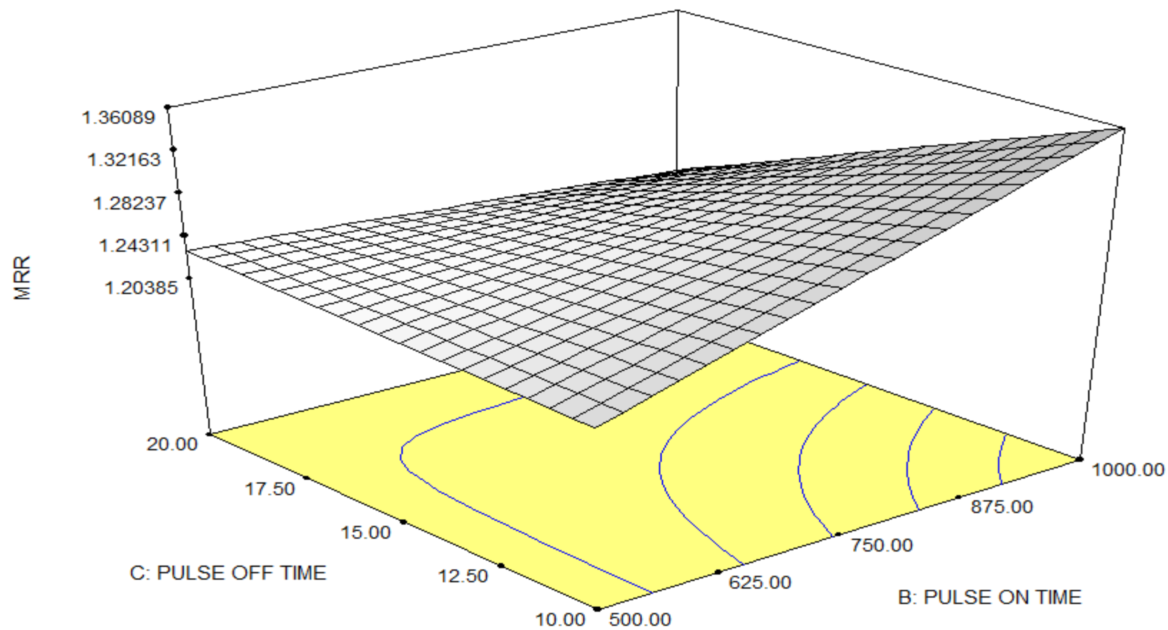


Figure 4.14 Interaction plot between pulse on time and pulse off for MRR

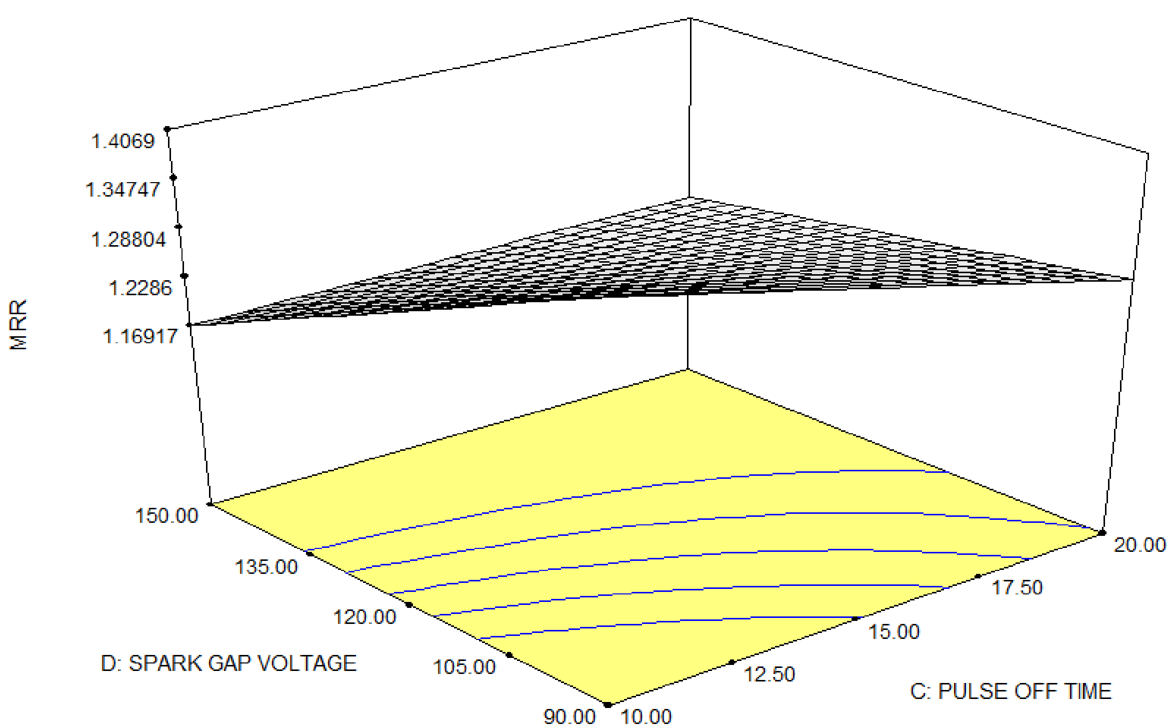


Figure 4.15 Interaction plot between spark gap voltage and pulse off for MRR

4.4.2 Effect Of Process Parameters On TWR

In this section, impact of process parameters on response variable(TWR) is studied. Plots for effect of process parameter as individual and as well as interaction of one to other on TWR are shown in fig from 4.16 to 4.21. TWR was affected by mainly Peak current(I_p),Pulse off time(T_{OFF}), Spark gap voltage (V). TWR is increased from 0.0372 to 0.1372 mg/min as peak current was increased from 7 to 15 A. Higher peak current as input parameter means higher applied energy results in higher TWR While as pulse off time is increased TWR was decreased, it`s because, enlarging the length of time span for pulse off decrease the number of sparks between the gap of tool and work-piece. As studied in previous papers [Md. Ashikur Rahman Khan, 2015]. Since pulse on time and pulse off time demonstrated the higher percentage contribution when contrasted with the other two factors they can be viewed as most significant to the TWR.

Two interactions have been found to be considerable $I_p \times T_{off}$ and $I_p \times SV$ as shown in Figures from 4.9 to 4.15. Optimum response can be attained when the parameters are set at; I_p=11A, T_{on}= 750 mu, T_{off} = 15 mu, SV= 120V.

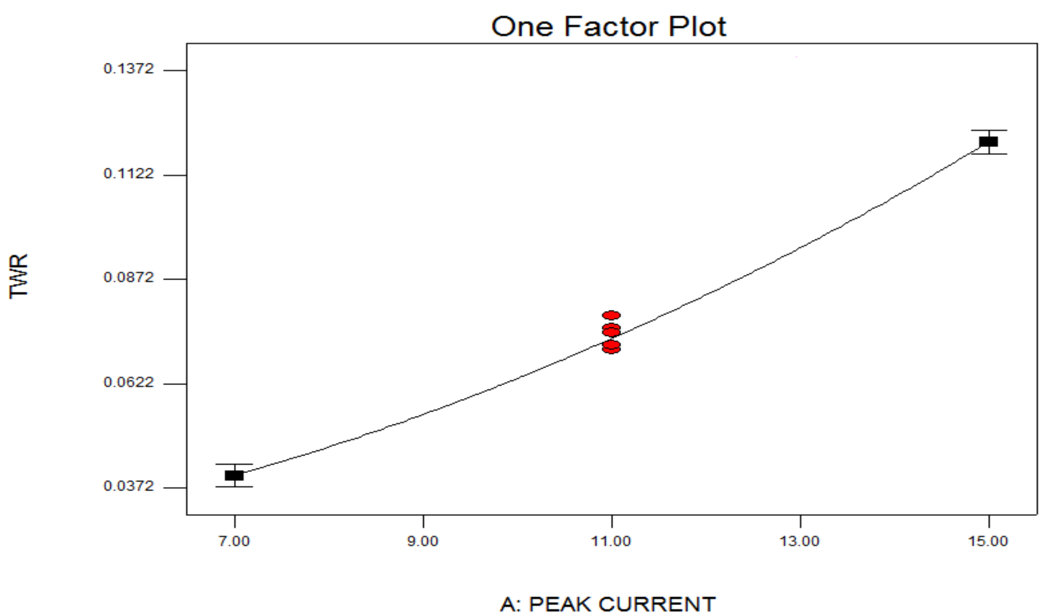


Figure 4.16 Effect of peak current on MRR

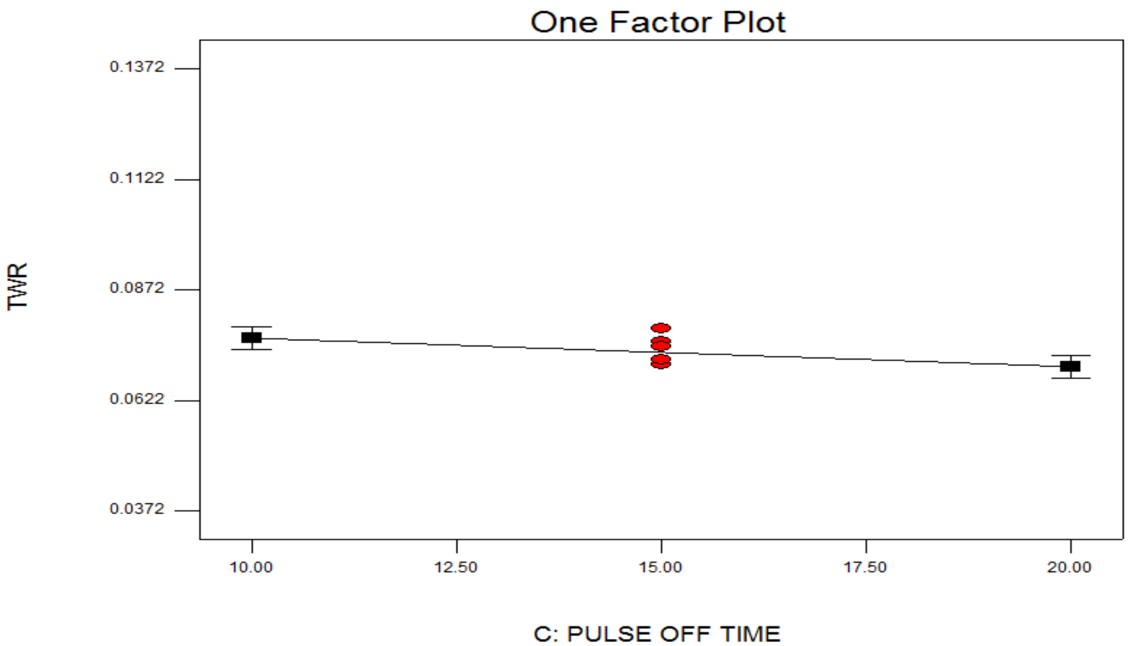


Figure 4.17 Effect of pulse off time on TWR

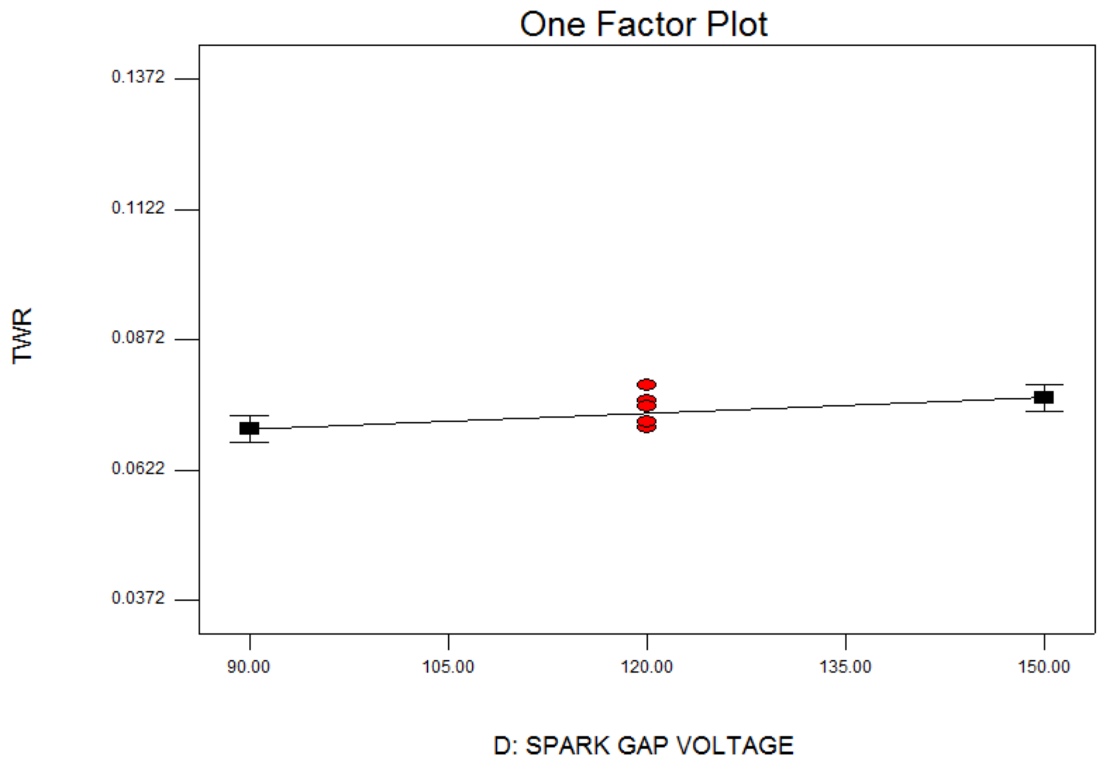


Figure 4.18 Effect of spark gap voltage on TWR

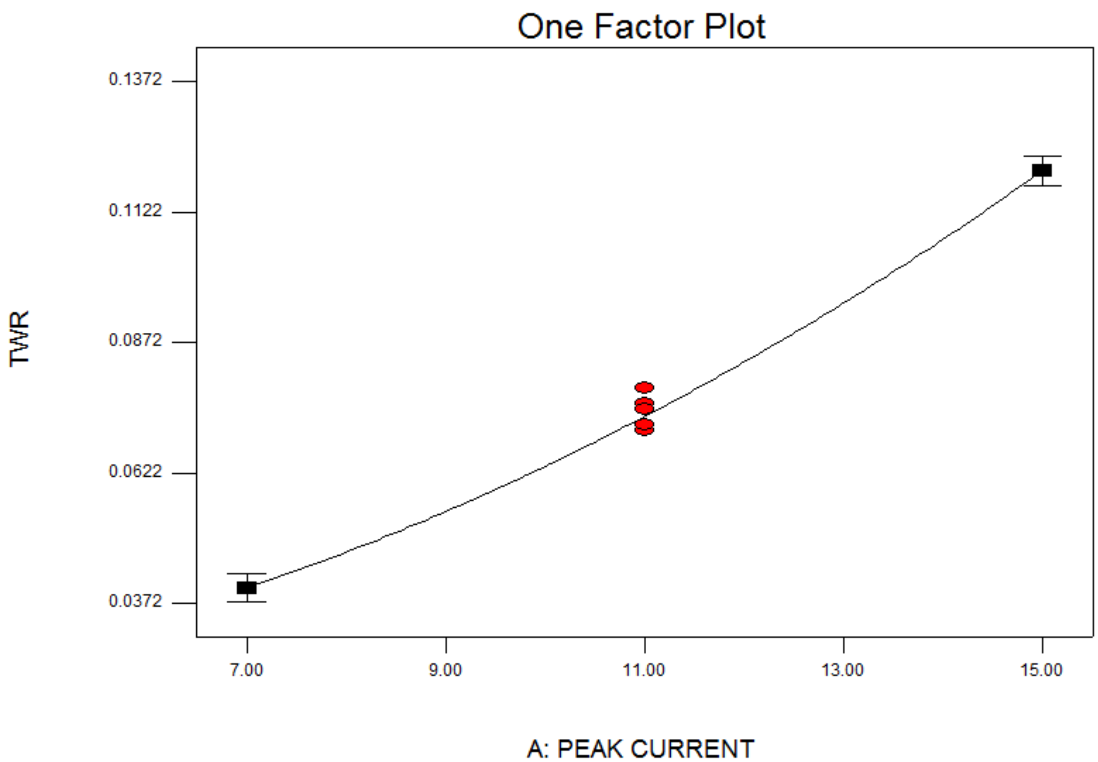


Figure 4.19 Effect of peak current^2 on TWR

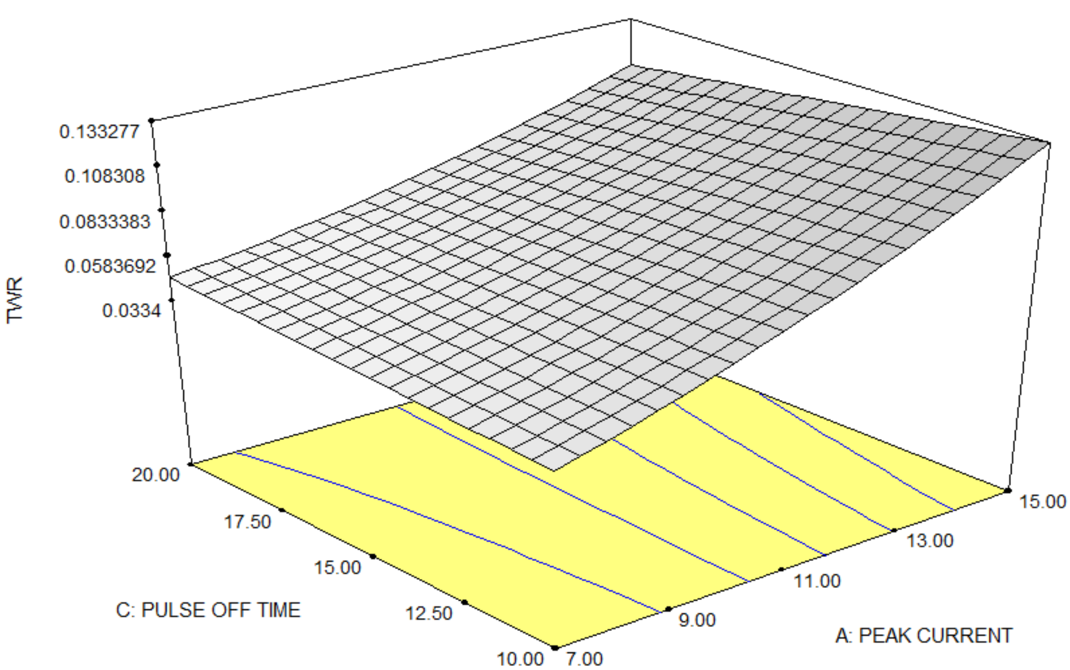


Figure 4.20 Interaction plot between peak current and pulse off for TWR

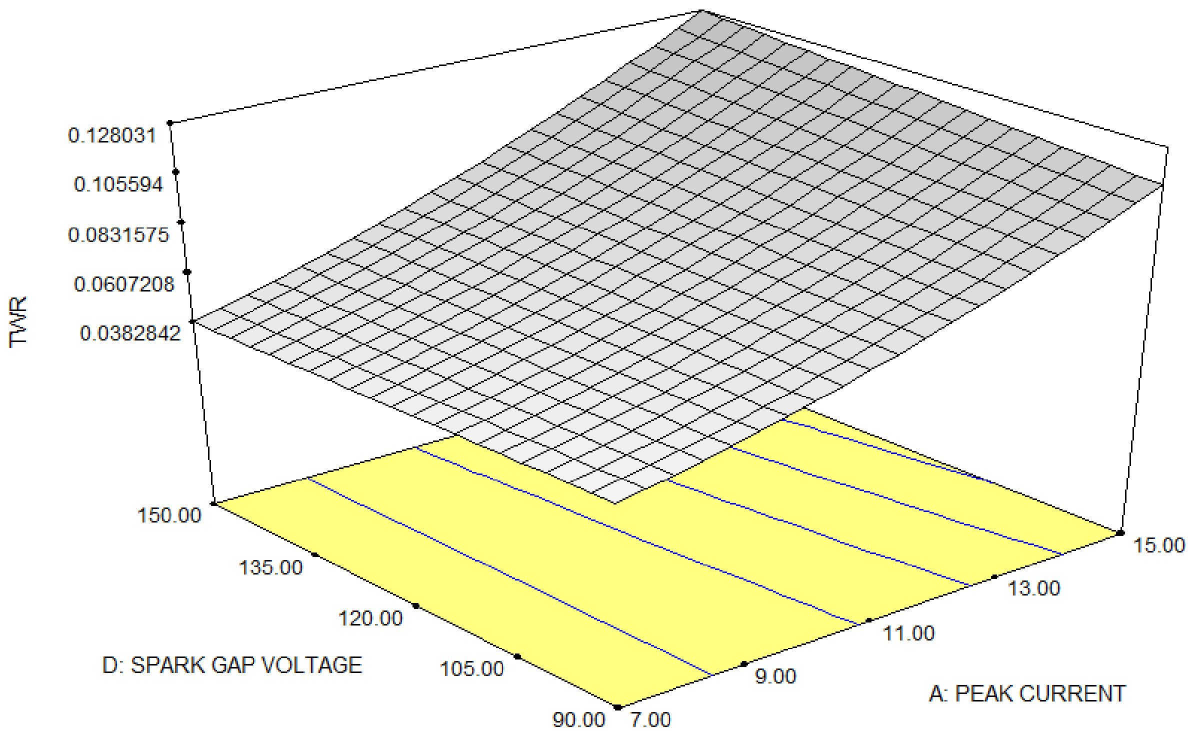


Figure 4.21 Interaction plot between peak current and spark gap voltage for TWR

4.4.3 Effect Of Process Parameters On SR

Plots for effect of process parameter as individual and as well as interaction of one to other on SR are shown in fig from 4.22 to 4.29. SR was affected by mainly Peak current(I_p),Pulse off time(T_{OFF}), Spark gap voltage (V). SR is increased from 1.136 to 3.912 µm as peak current and pulse on time was increased from 7 to 15 A and 500 to 1000 µm respectively. Higher peak current as input parameter means higher applied energy, which means higher crater formation, higher cracks and sometimes arcing also occurs. And as pulse off time is increased SR decreases. It may be because, enlarging the length of time span of pulse off decrease the number of sparks between the gap of tool and work-piece. Since pulse on time and pulse off time demonstrated the higher percentage contribution when contrasted with the other two factors they can be viewed as most significant to the SR.

Three interactions have been found to be considerable $I_p \times T_{on}$, $I_p \times T_{off}$ and $I_p \times SV$ as shown in Figures from 4.22 to 4.29. Optimum response can be attained when the parameters are set at;

I_p=11A, T_{on}= 750 mu, T_{off} = 15 mu, SV= 120V.

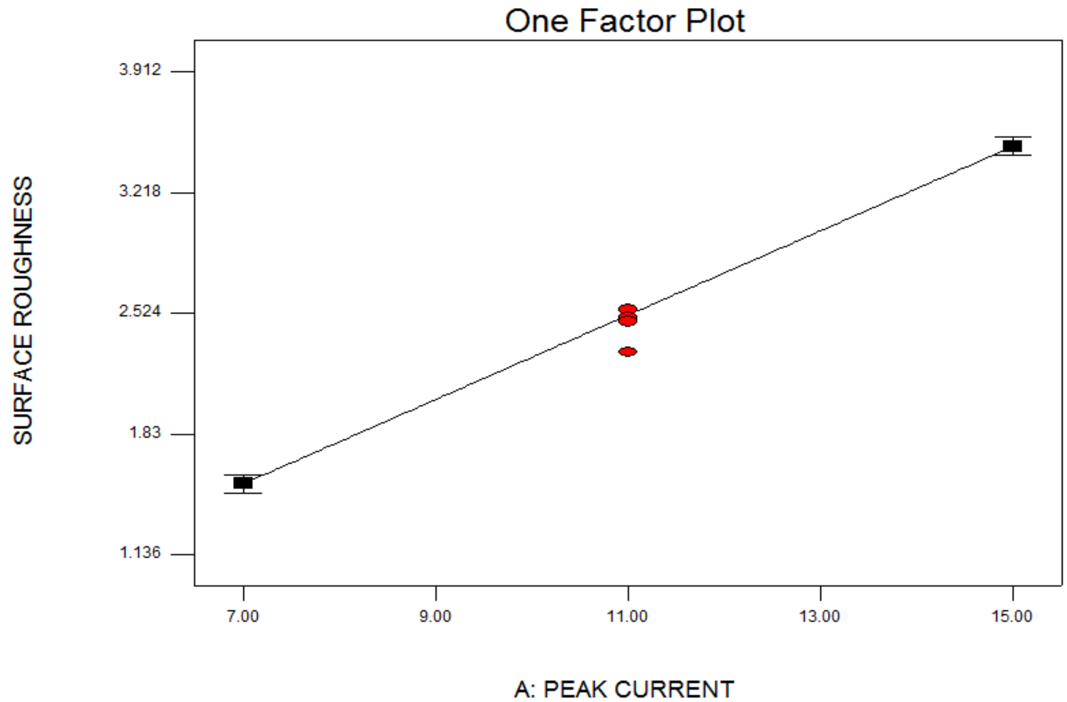


Figure 4.22 Effect of peak current on SR

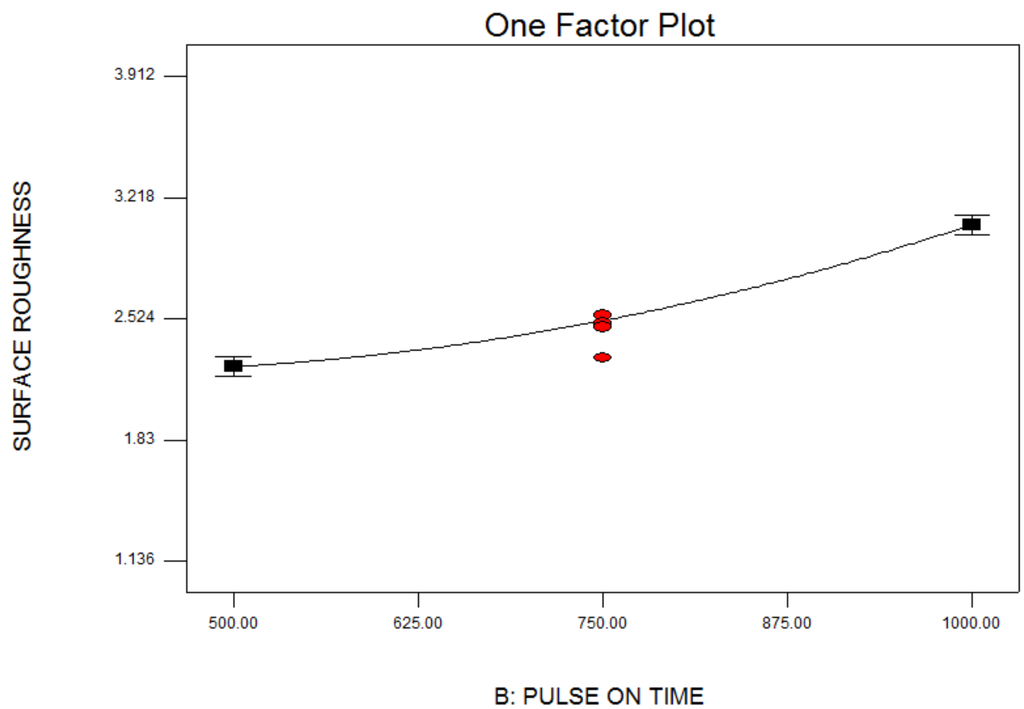


Figure 4.23 Effect of pulse on time SR

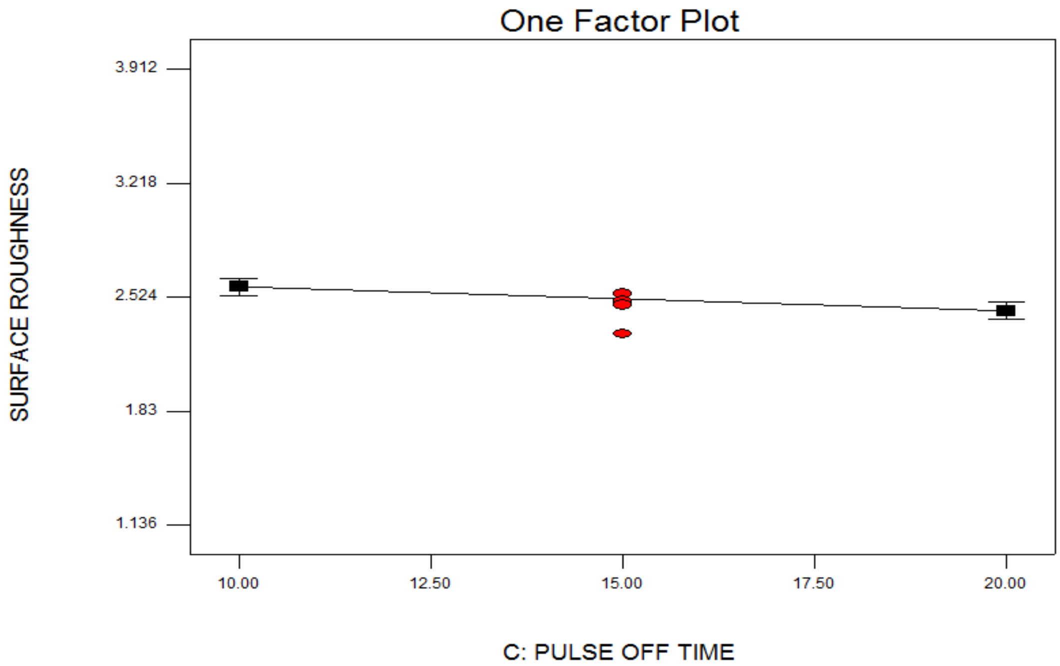


Figure 4.24 Effect of pulse off time SR

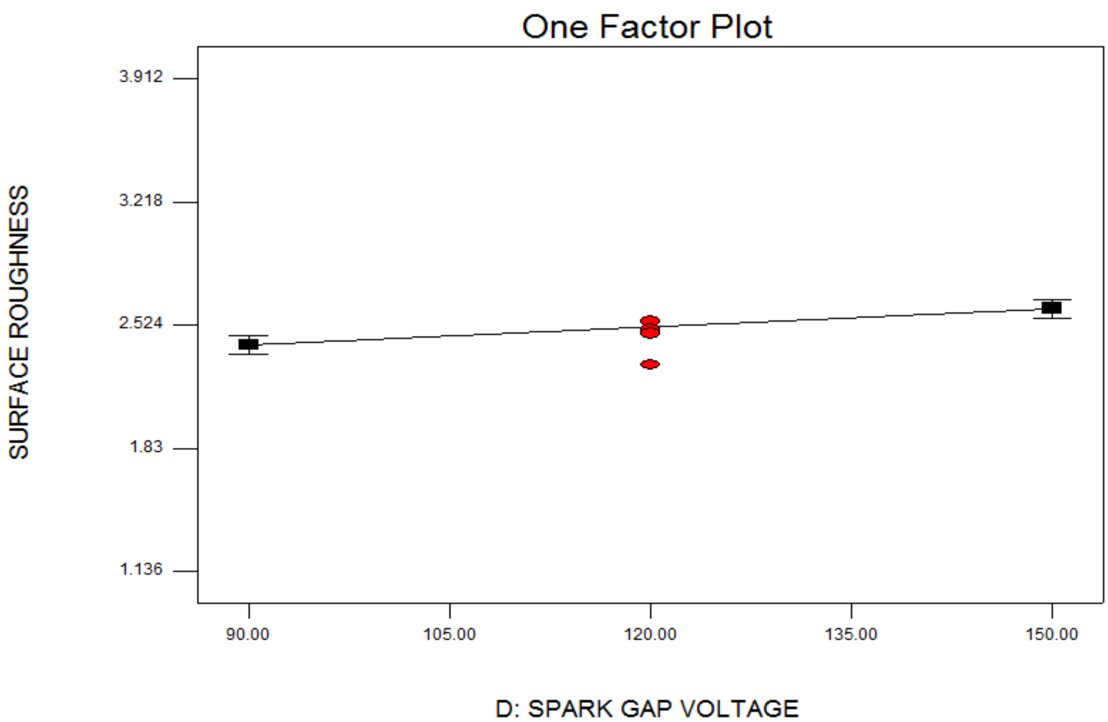


Figure 4.25 Effect of spark gap voltage SR

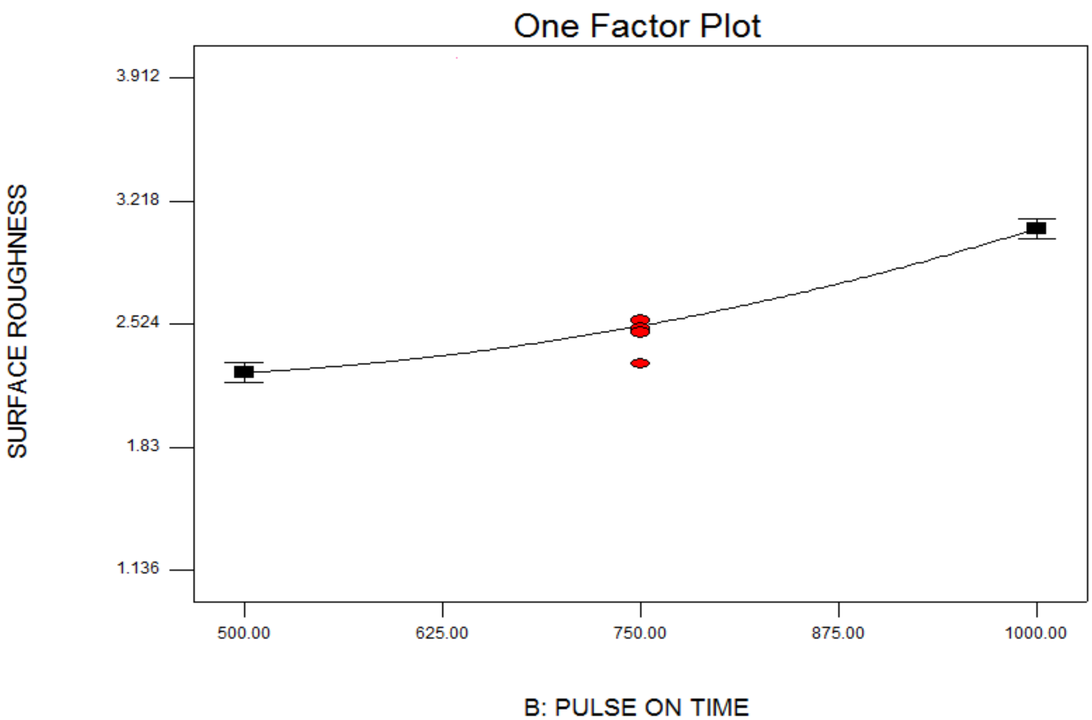


Figure 4.26 Effect of pulse on time2 SR

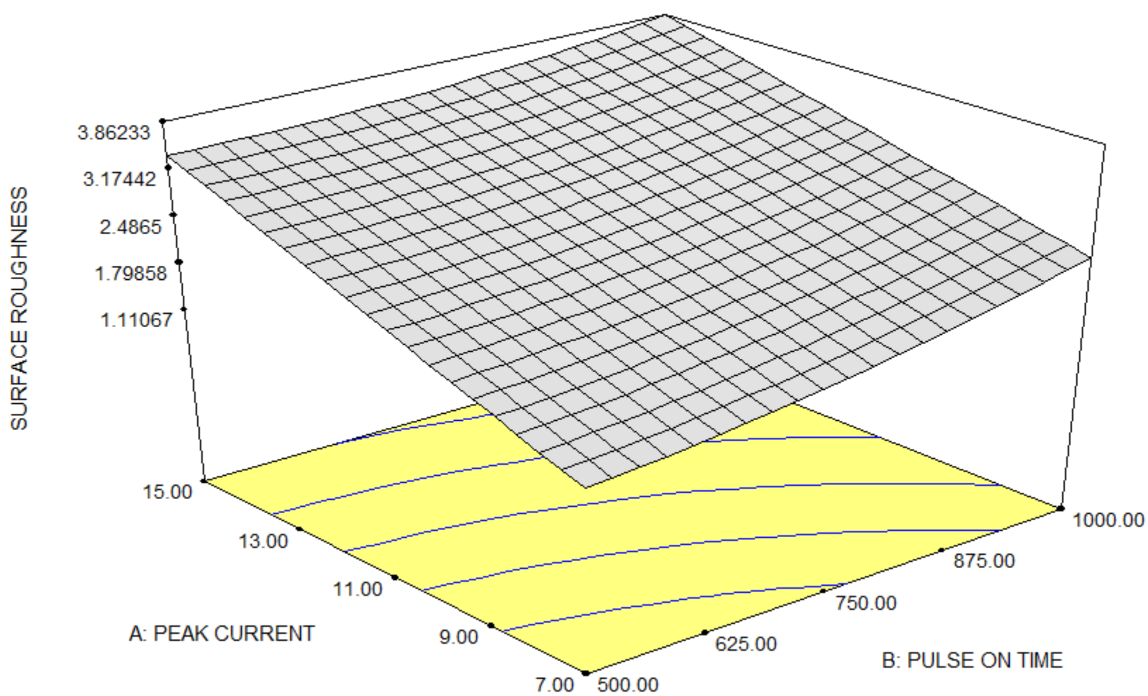


Figure 4.27 Interaction plot between peak current and pulse on time for SR

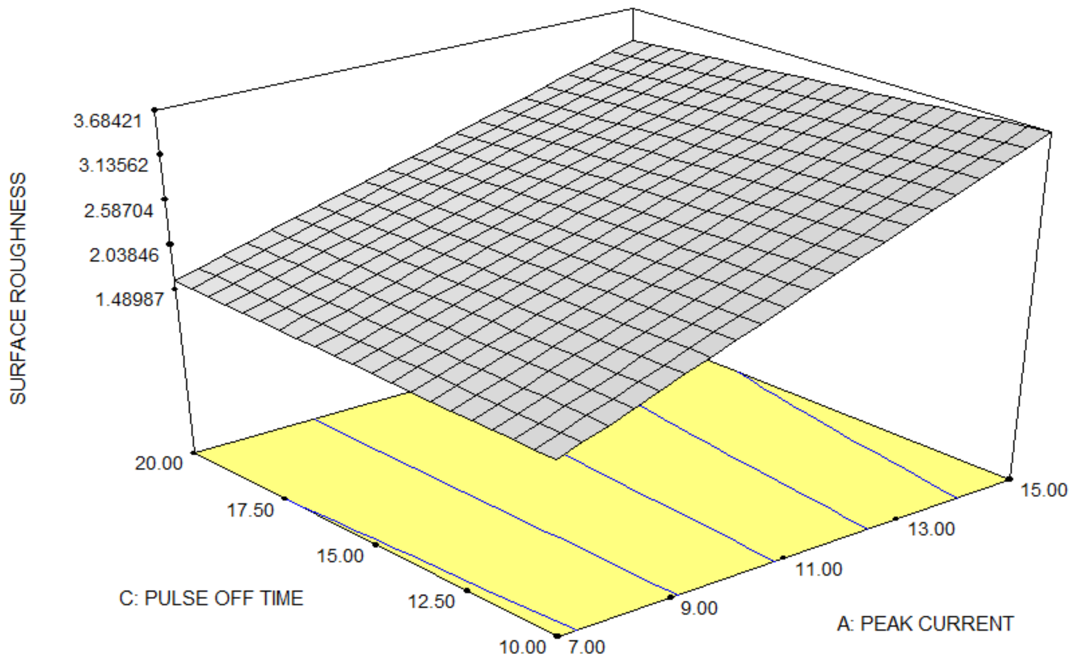


Figure 4.28 Interaction plot between peak current and pulse off time for SR

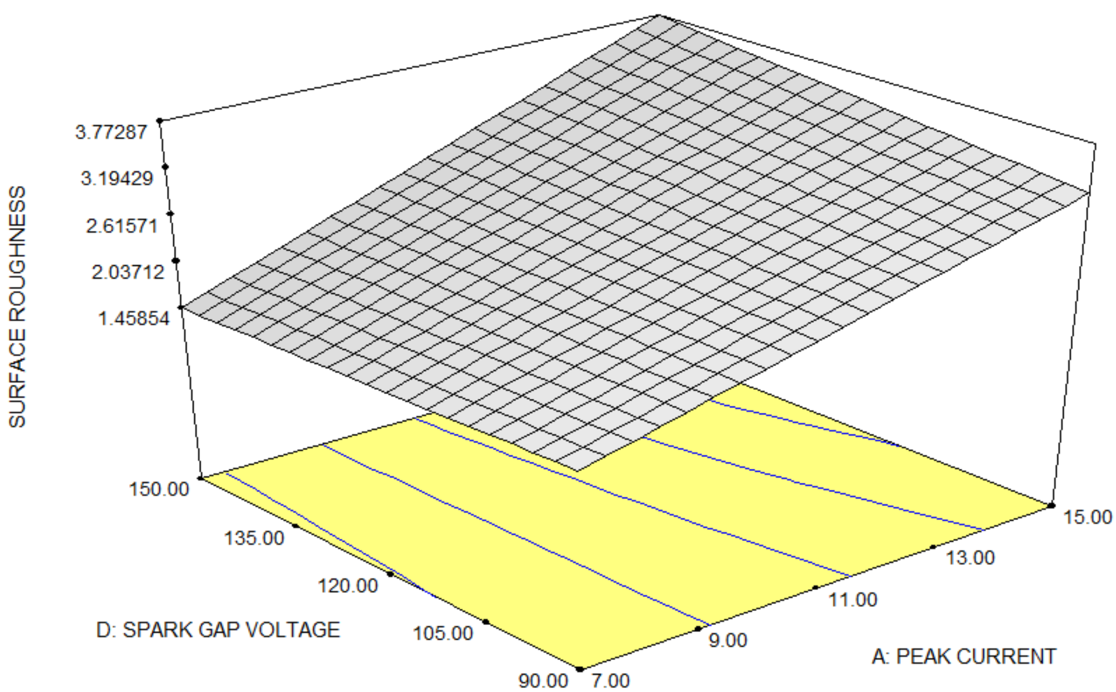


Figure 4.29 Interaction plot between peak current and spark gap voltage for SR

4.4.4 Effect Of Process Parameters On MH

Plots for effect of process parameter as individual and as well as interaction of one to other on MH are shown in fig from 4.30 to 4.33. MH was affected mainly by Peak current (I_p),Pulse off time (T_{OFF}). SR is increased from 1408.39 to 1841.35 HV. On increasing the pulse on time from 500 to 1000 µm it was found that hardness decreased as studied by [NOOR ZAMAN KHAN, 2013]. Since it is known that as pulse on time increases number of sparks in one cycle increases which gives less time to material for resolidification, so higher crater formation, higher cracks, voids and poke marks.

One interaction has been found to be considerable $I_p \times T_{on,}$ as shown in Figures from 4.33.

Optimum response can be attained when the parameters are set at; I_p=11A, T_{on}= 750 mu, T_{off} = 15 mu, SV= 120V.

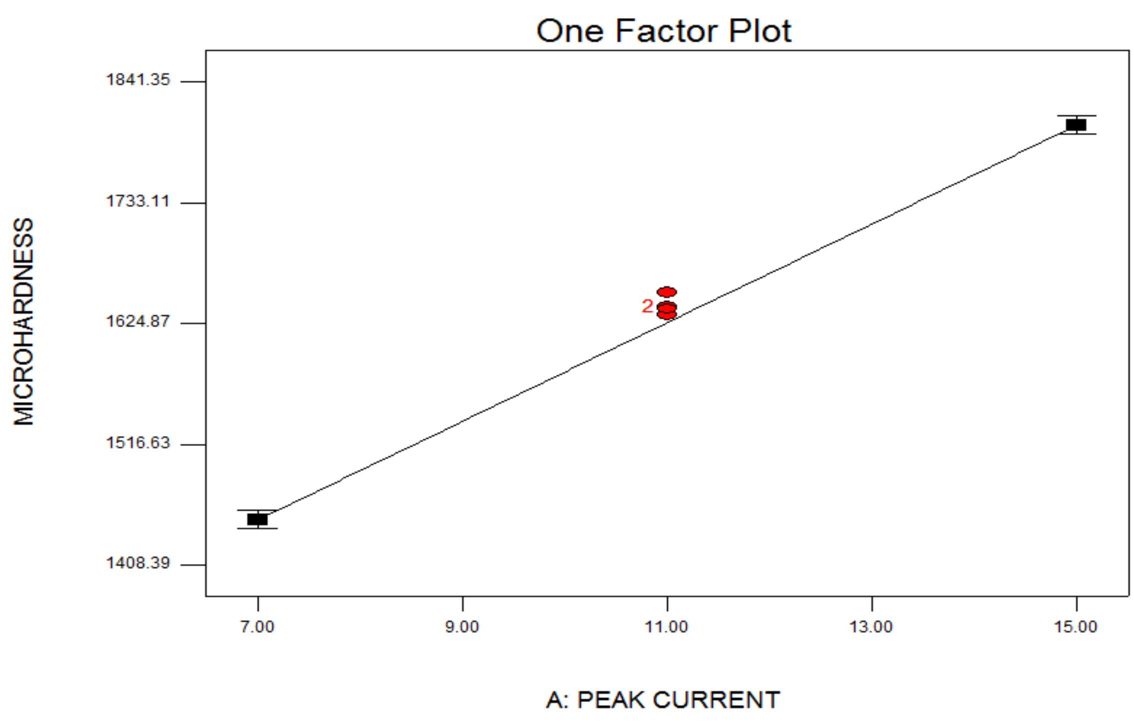


Figure 4.30 Effect of peak current on MH

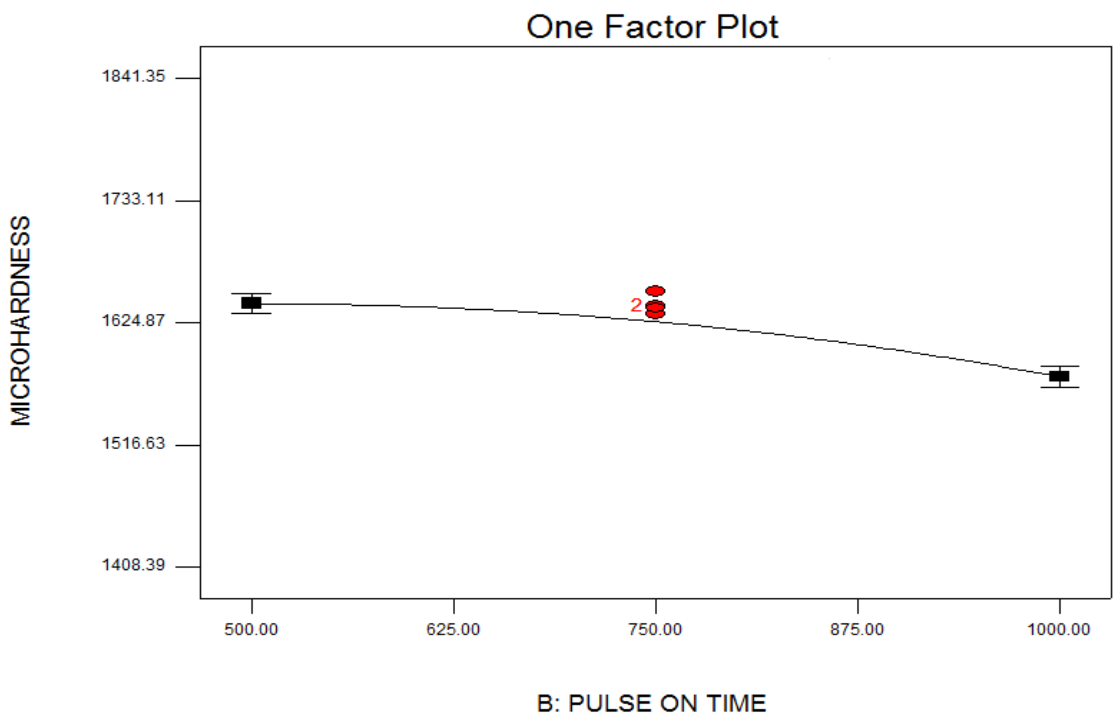


Figure 4.31 Effect of pulse on time MH

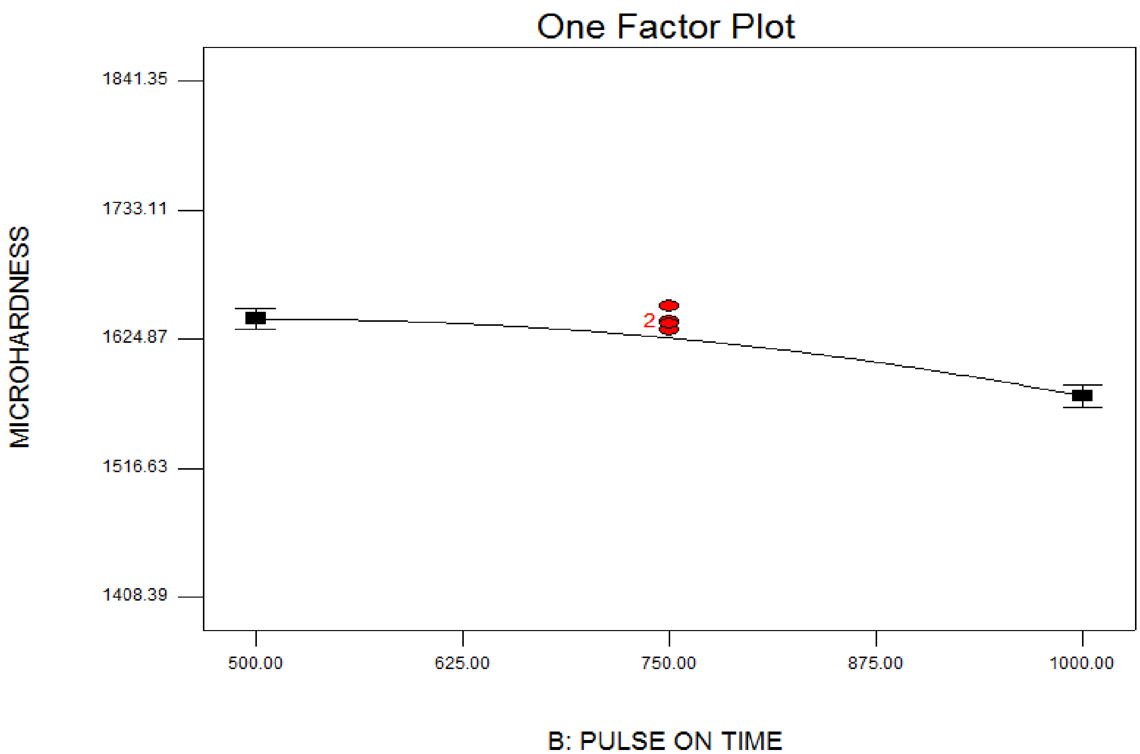


Figure 4.32 Effect of pulse on time2 MH

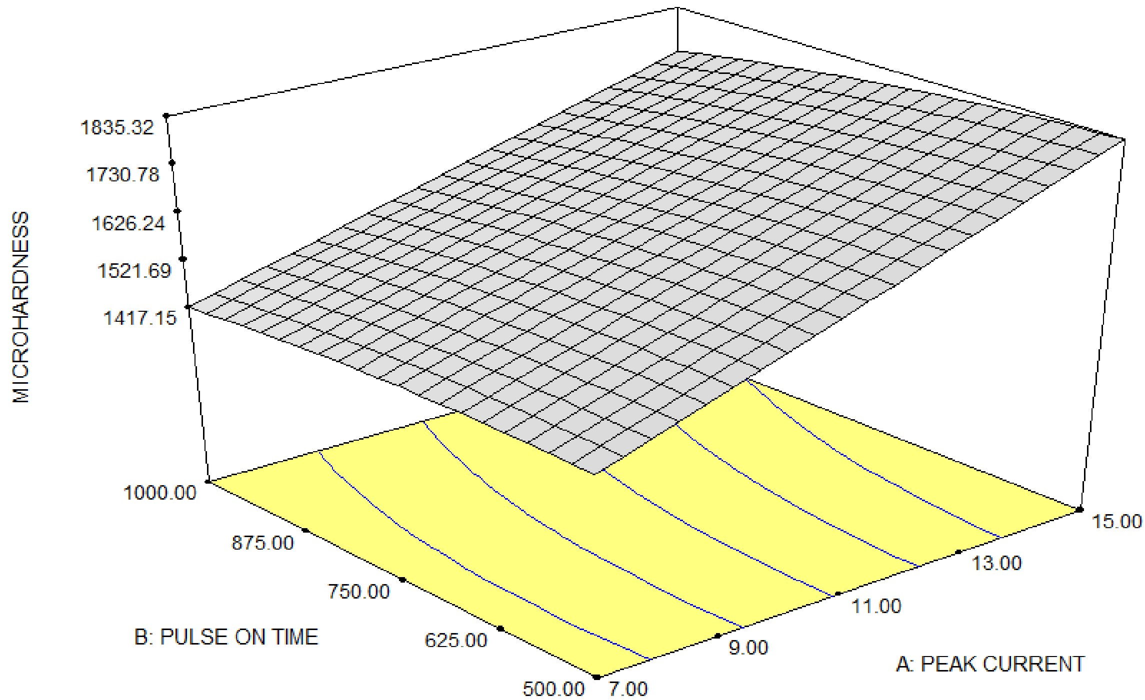


Figure 4.33 Interaction plot between peak current and pulse on time for MH

4.5 Microstructure Characteristics And Material Transformation Analysis Of Machined Surface

Present research work is also concentrated on inspection of integrity of surface of work surface after machining on Die-Sink EDM. In experiments, It was found that pulse on time and peak current affects the surface integrity and surface topography most. At higher pulse on time and peak current, deep-wide overlapping craters, debris, micro cracks and recast layer forms. Peak current is responsible for higher energy input while pulse on time is responsible for more number sparks in one cycle. Discharge energy causes melting of work-piece and debris are formed which are flushed away from the gap between tool and work-piece with the help of open type flushing.

It is known that surface topography affects the surface roughness and surface roughness affects service life of the component in terms of fatigue life. Better the surface roughness results in better fatigue life. This kind of relationship exists with respect of fatigue life. Aim of this study is to achieve better surface quality in given design. For analysis of surface topography, RSM is applied.

The following subsections investigate the effect of process parameters on microstructure and the thickness of recast layer produced in the machined Ti-6Al-7Nb samples

4.5.1 Material and test condition

During the experimentation, parameters such as peak current, pulse on time, pulse off time, and spark gap voltage were varied to scrutinize their effects on surface integrity of Ti-6Al-7Nb. After Die-Sink EDM, the metallographic investigations of the machined samples were made using scanning electron microscope (SEM). The samples were cleaned with acetone (CH3)2CO before being investigated on SEM.

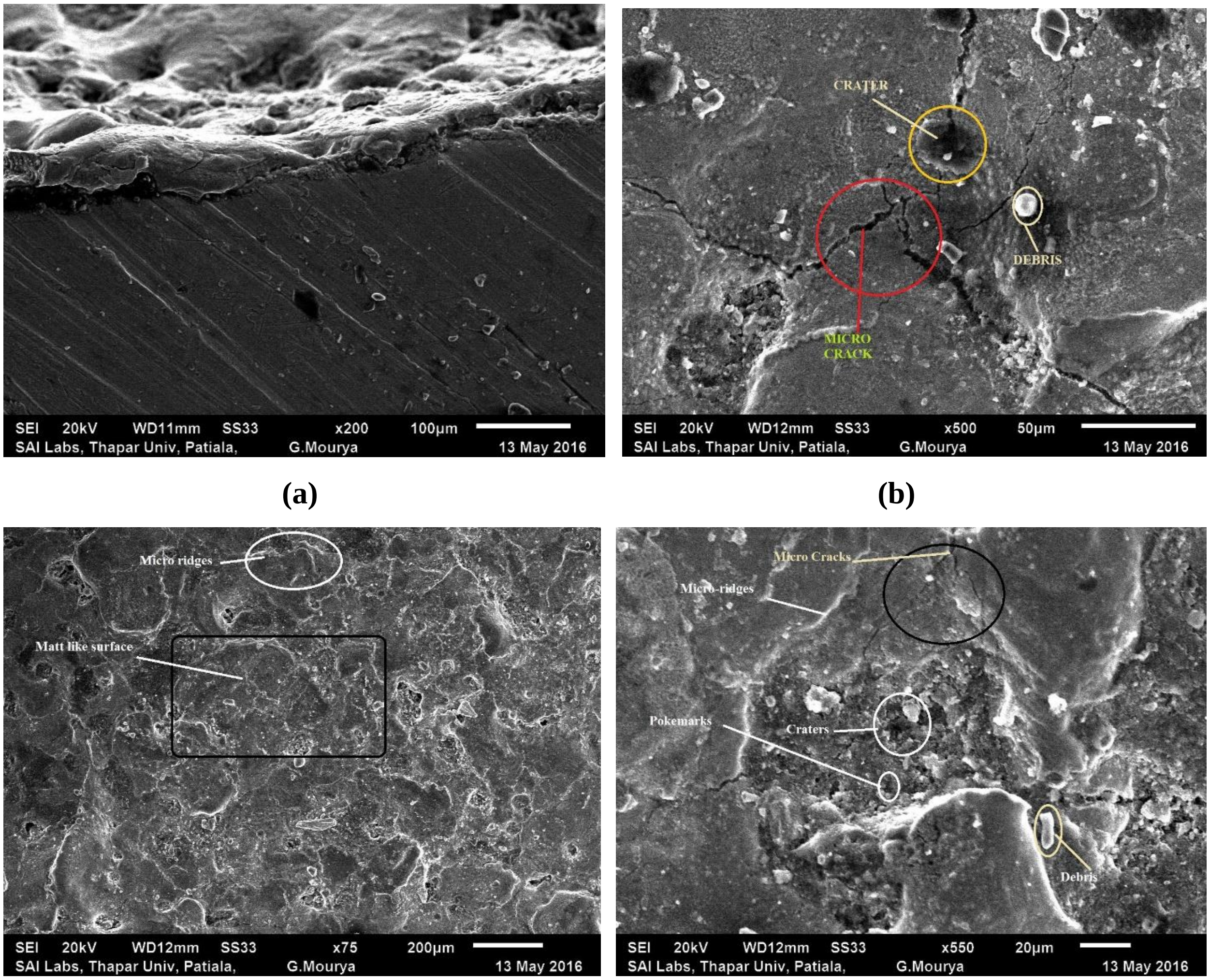
4.5.2 Results and discussion on machined surface topography and micro-cracks creation

Nature of machined surface and life of machined surface is mainly defined by nature or type of surface topography of machined surface. And surface topography is mainly affected by input parameters or process parameters such as peak current, pulse off time, pulse on time, spark gap voltage. Images formed by SEM reveals that surface topography contains micro cracks, crates, micro ridges, globules of debris, and spherical particles.

Applied high discharge energy from peak current causes the metal to melt and molten metal takes spherical shapes, because of lowest surface tension at its surface. Higher pulse on time increases the number of sparks in the given cycle, when number of sparks is increased, time for resolidification of molten material decreases which results in formation of higher craters on the surface. Some part of heat is carried away by dielectric fluid.

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].

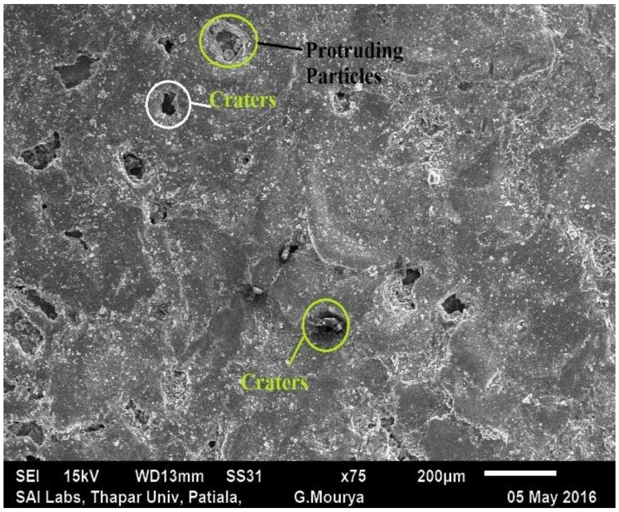
Here, the SEM images of the Ti-6Al-7Nb samples which are machined on Die-Sink EDM, are shown below



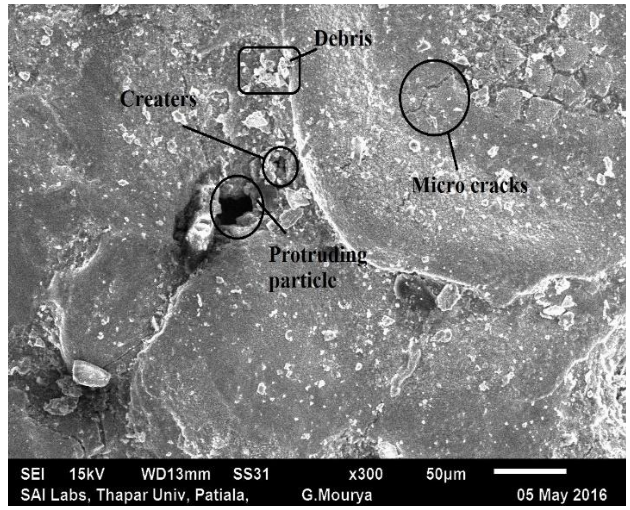
(a) **(b)**

(c) **(d)**

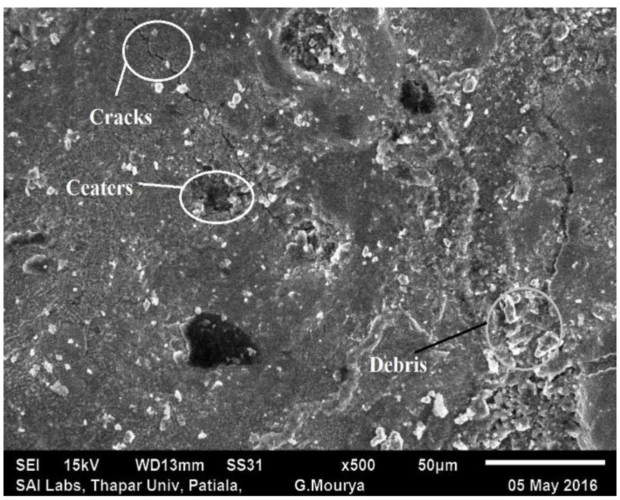
Figure 4.34 SEM micrographs of Ti-6Al-7Nb samples at different zoom(X) (a, b, c, d) observed with Cracks, Craters and Debris at peak current=7, pulse on time = 500 mu, pulse off time = 15 mu, Spark gap voltage= 120 V and and Ra= 1.136 µm. [Sai Lab, Thapar University, Patiala]



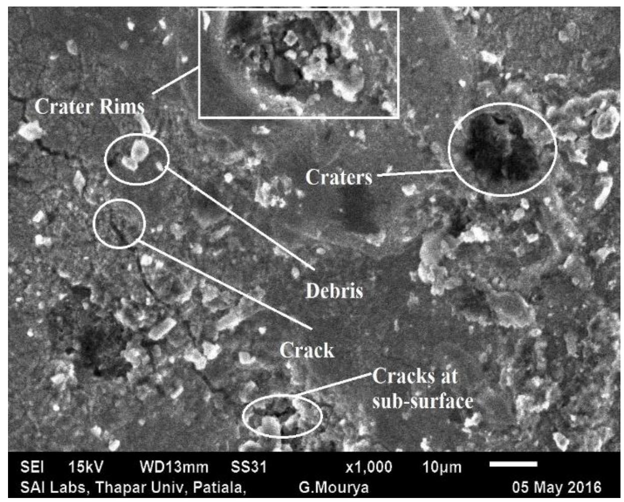
(a)



(b)

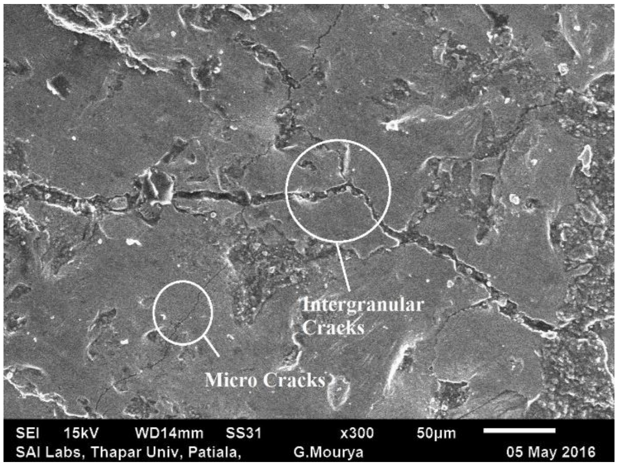


(c)

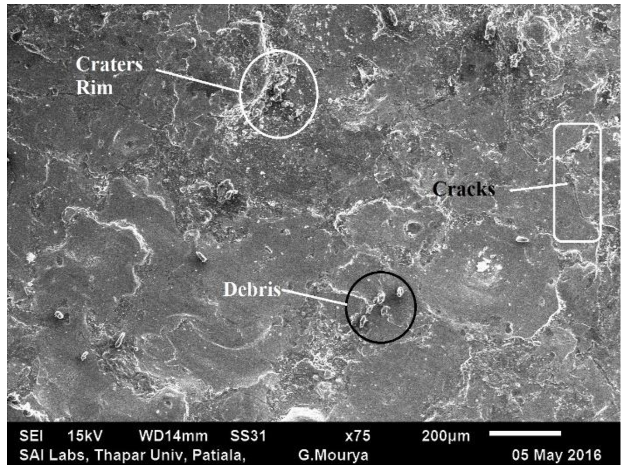


(d)

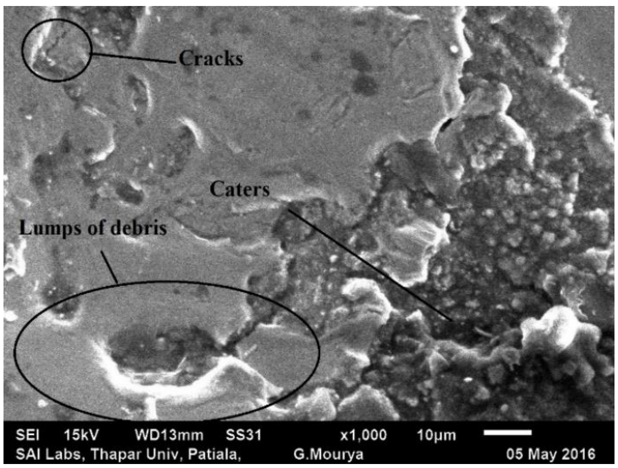
Figure 4.35 SEM micrographs of Ti-6Al-7Nb samples at different zoom(X) (a, b, c, d) observed with Cracks, Craters and Debris at peak current=7, pulse on time = 1000 mu, pulse off time = 15 mu, Spark gap voltage= 120 V and and Ra= 1.136 µm. [Sai Lab, Thapar University, Patiala]



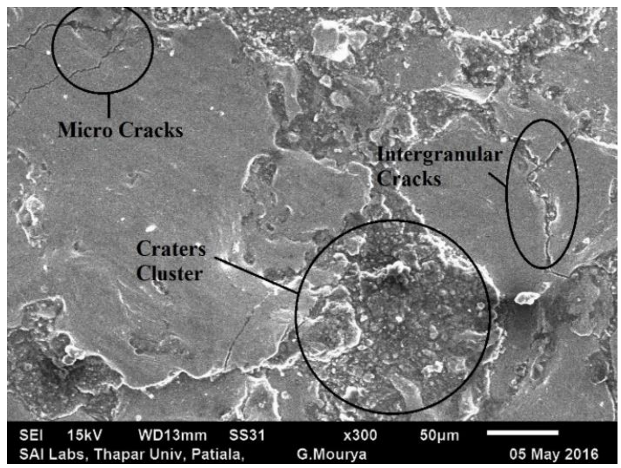
(a)



(b)



(c)



(d)

Figure 4.36 SEM micrographs of Ti-6Al-7Nb samples at different zoom(X) (a, b, c, d) observed with Cracks, Craters and Debris at peak current=11, pulse on time = 500 mu, pulse off time = 10 mu, Spark gap voltage= 120 V and and Ra= 2.24 µm. [Sai Lab, Thapar University, Patiala]

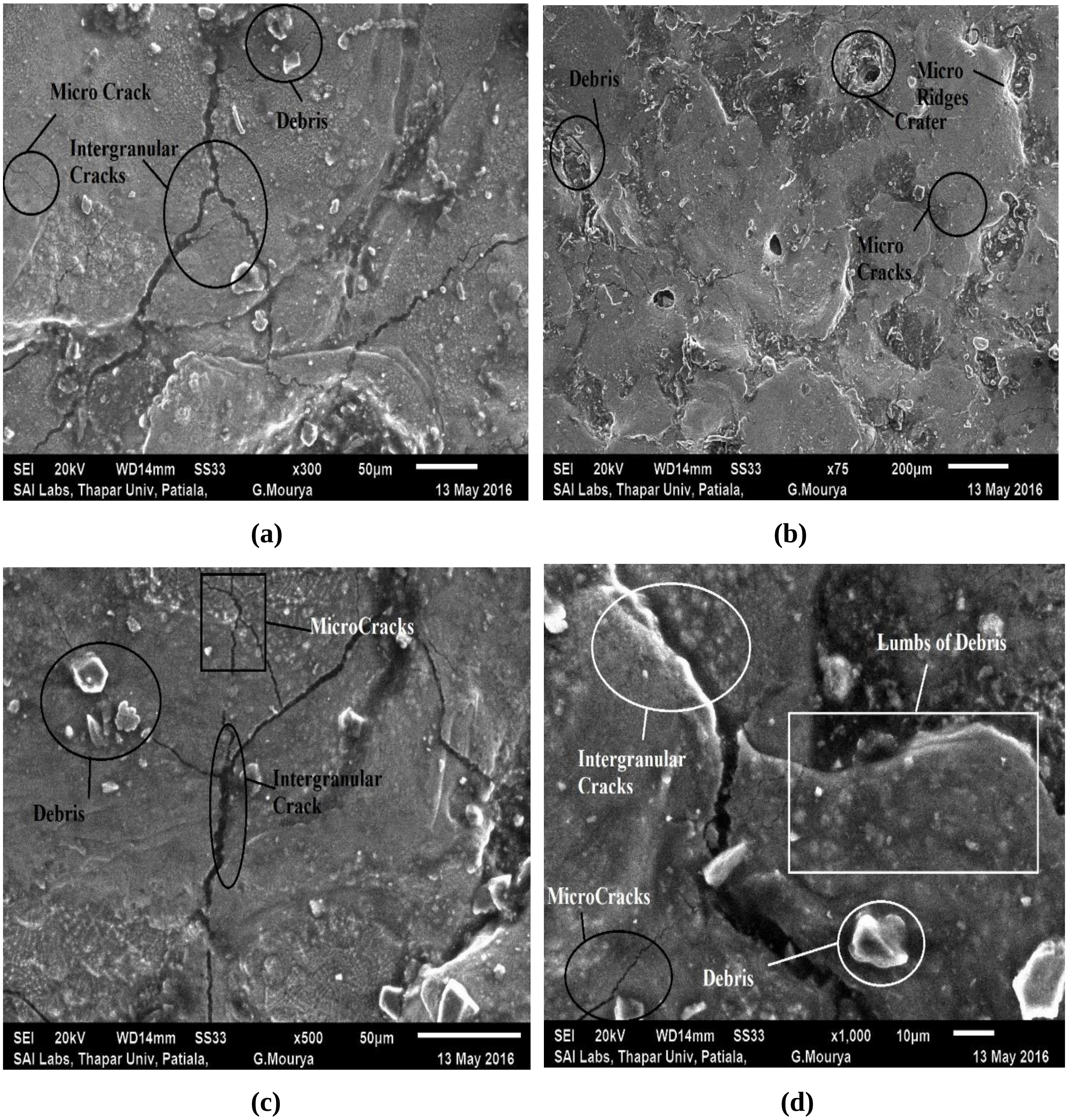


Figure 4.37 SEM micrographs of Ti-6Al-7Nb samples at different zoom(X) (a, b, c, d) observed with Cracks, Craters and Debris at peak current=11, pulse on time = 750 mu, pulse off time = 15 mu, Spark gap voltage= 120 V and and Ra= 2.495 µm. [Sai Lab, Thapar University, Patiala]

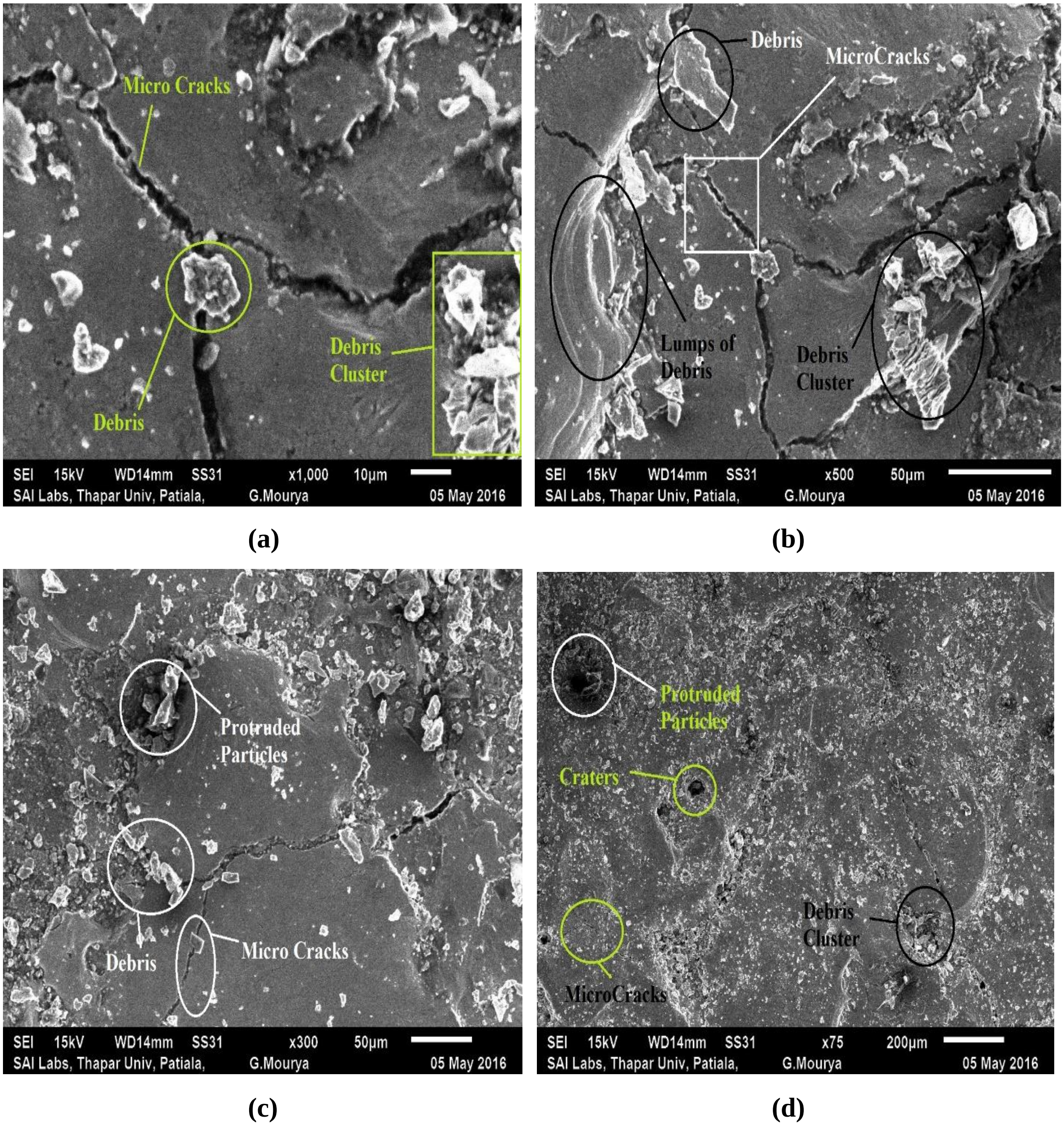
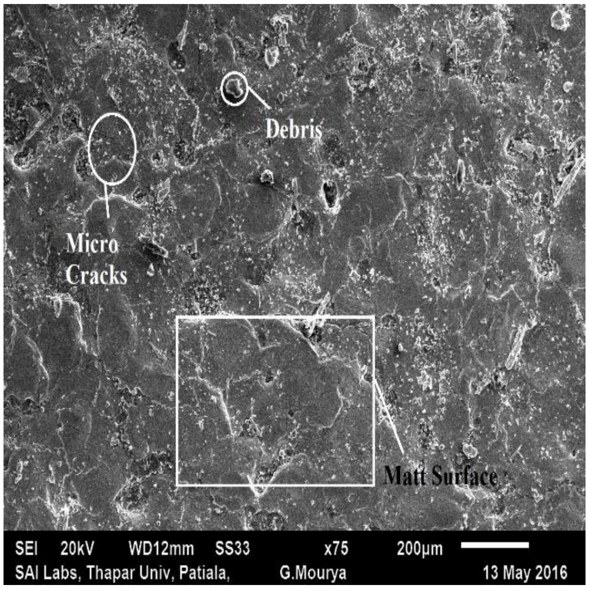
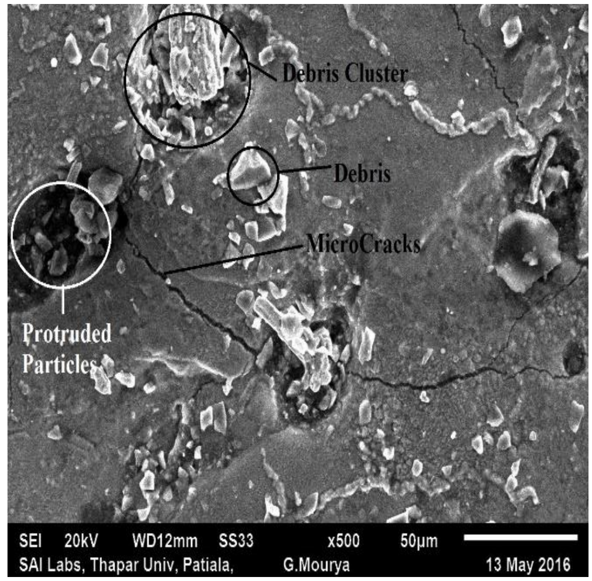


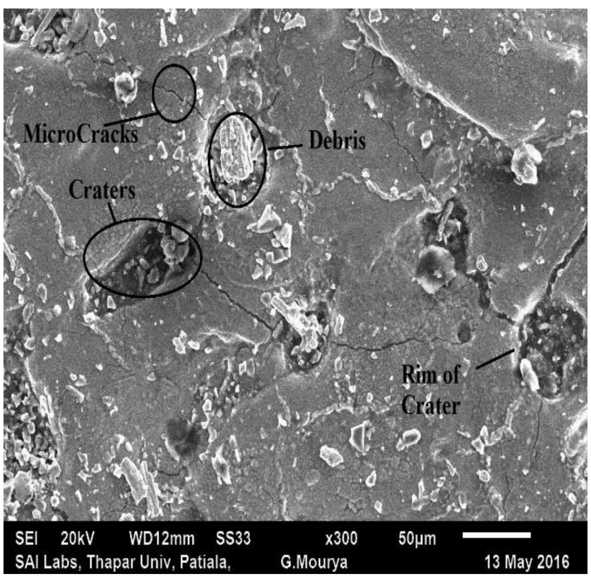
Figure 4.38 SEM micrographs of Ti-6Al-7Nb samples at different zoom(X) (a, b, c, d) observed with Cracks, Craters and Debris at peak current=11, pulse on time = 1000 mu, pulse off time = 10 mu, Spark gap voltage= 120 V and and Ra= 3.19 µm. [Sai Lab, Thapar University,Patiala]



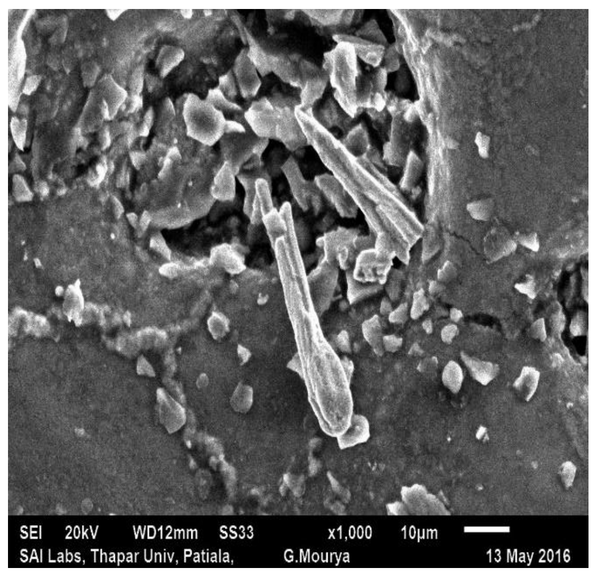
(a)



(b)



(c)



(d)

Figure 4.39 SEM micrographs of Ti-6Al-7Nb samples at different zoom(X) (a, b, c, d) observed with Cracks, Craters and Debris at peak current=15, pulse on time = 500 mu, pulse off time = 15 mu, Spark gap voltage= 120 V and and Ra= 3.48 µm. [Sai Lab, Thapar University, Patiala]

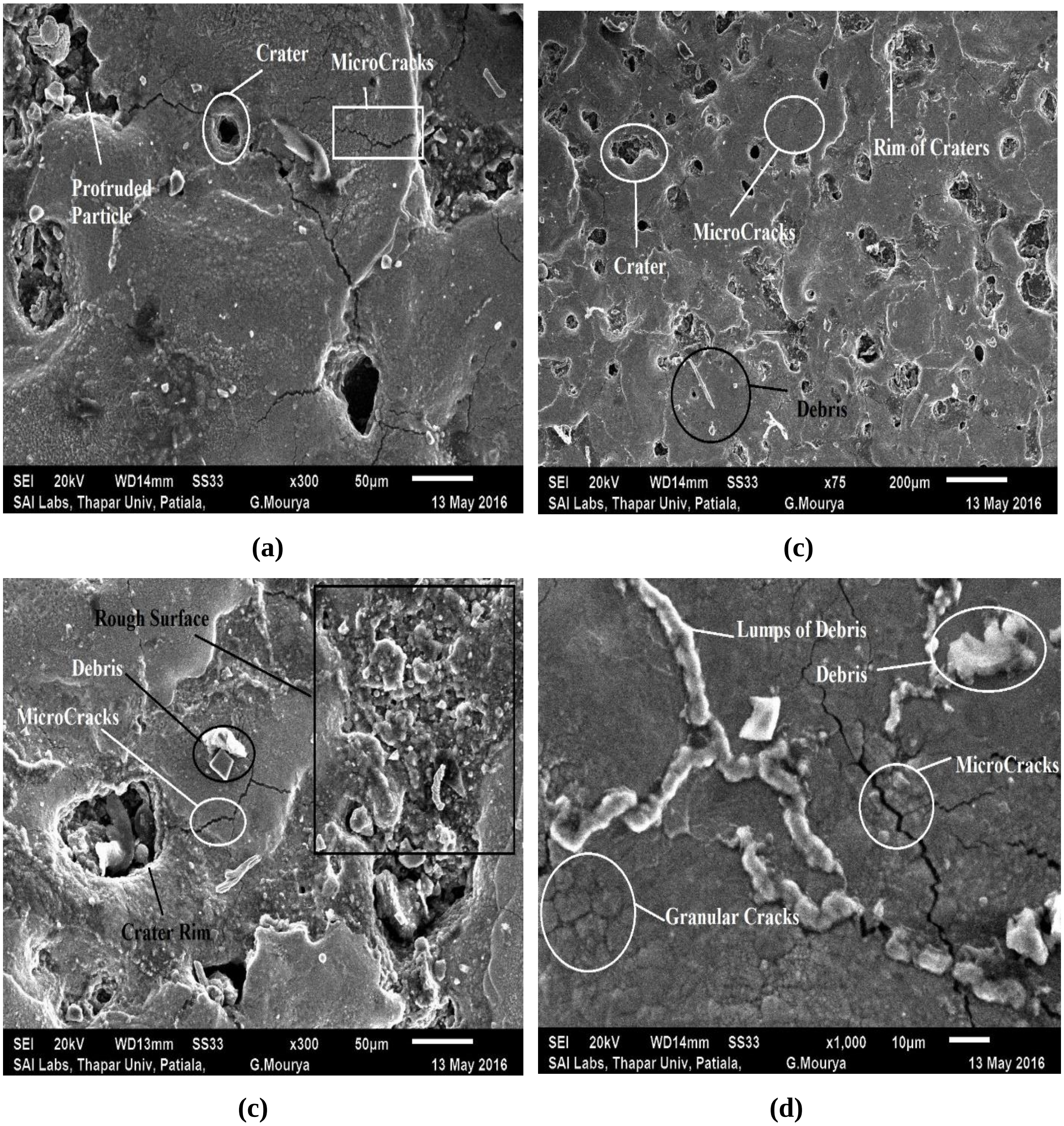


Figure 4.40 SEM micrographs of Ti-6Al-7Nb samples at different zoom(X) (a, b, c, d) observed with Cracks, Craters and Debris at peak current=15, pulse on time = 750 mu, pulse off time = 10 mu, Spark gap voltage= 120 V and and Ra= 3.721µm. [Sai Lab, Thapar University, Patiala]

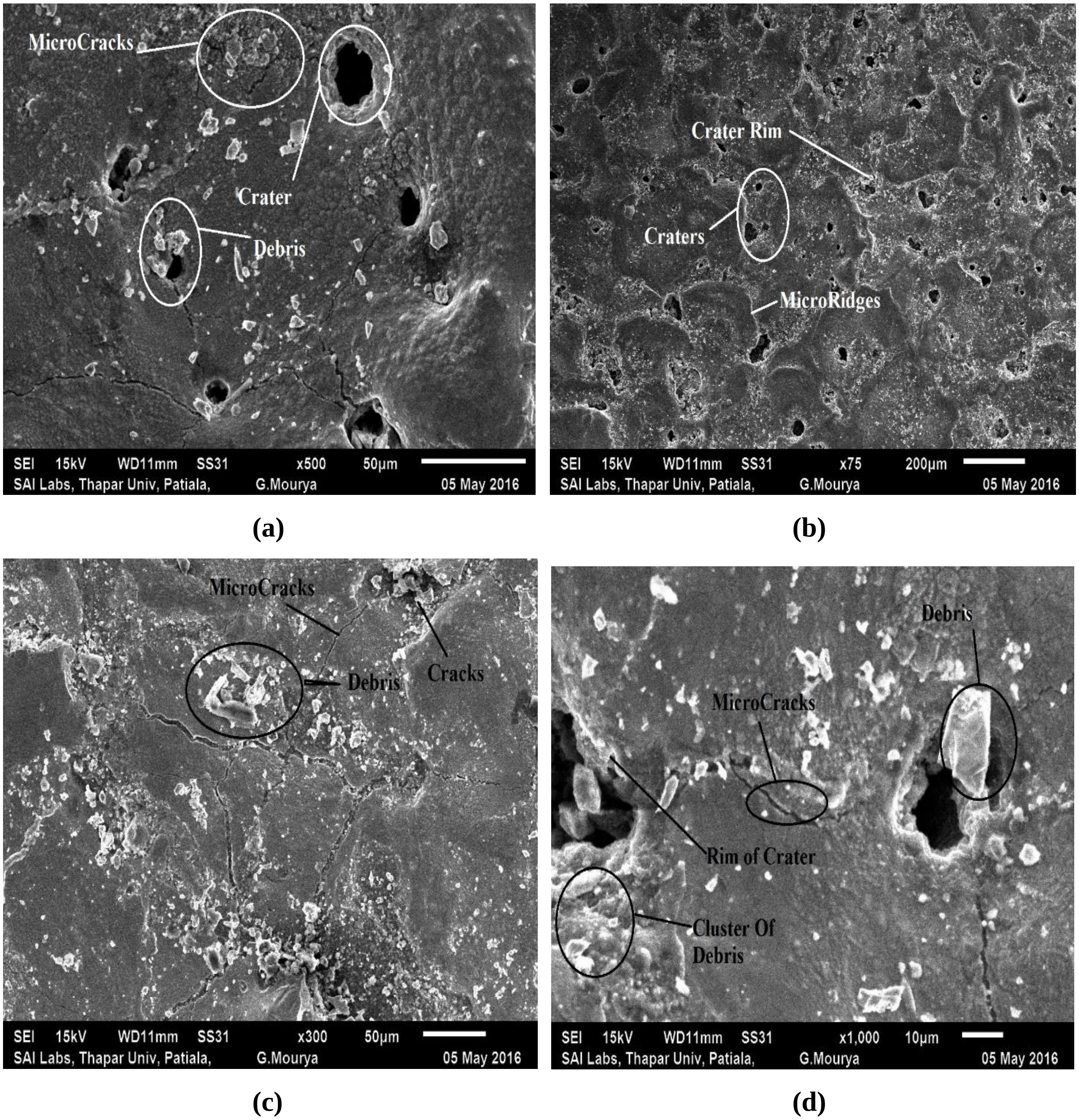


Figure 4.41 SEM micrographs of Ti-6Al-7Nb samples at different zoom(X) (a, b, c, d) observed with Cracks, Craters and Debris at peak current=15, pulse on time = 1000 mu, pulse off time = 15 mu, Spark gap voltage= 120 V and and Ra= 3.81 µm. [Sai Lab, Thapar University, Patiala]

4.5.3 Results And Discussion On Recast Layer

Recast layer can be seen at the cross section of work-piece after machining on Die Sink EDM. As the term (re + casting) defines in itself which means material melts due to high energy and re-solidifies on the surface of work-piece after machining done by EDM. This re casted material is not easy to remove from the machined surface. When molten material settle down on the surface of work-piece and re-solidifies in that time duration it transmits the heat to the surface of work-piece and this transmitted heat causes the formation of heat affected zone (HAZ).

Recast layer and heat affected zone can easily be seen at the cross section of the machined surface with the help of SEM. SEM magnifies the image at adverse level and let us show the surface at that magnification. HAZ forms just below the RL because heat is transmitted from the RL. Thickness of HAZ is changed with respect to the thickness of RL. Higher the thickness of RL results in higher the thickness of HAZ. Since energy totally depends on pulse on time and pulse off time so as discharge energy increases, thickness of HAZ also increases. It can be seen that RL layer forms in the non-uniform way on the surface. The micro cracks cleaving in the matrix have harmful 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 presence of micro-cracks 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].

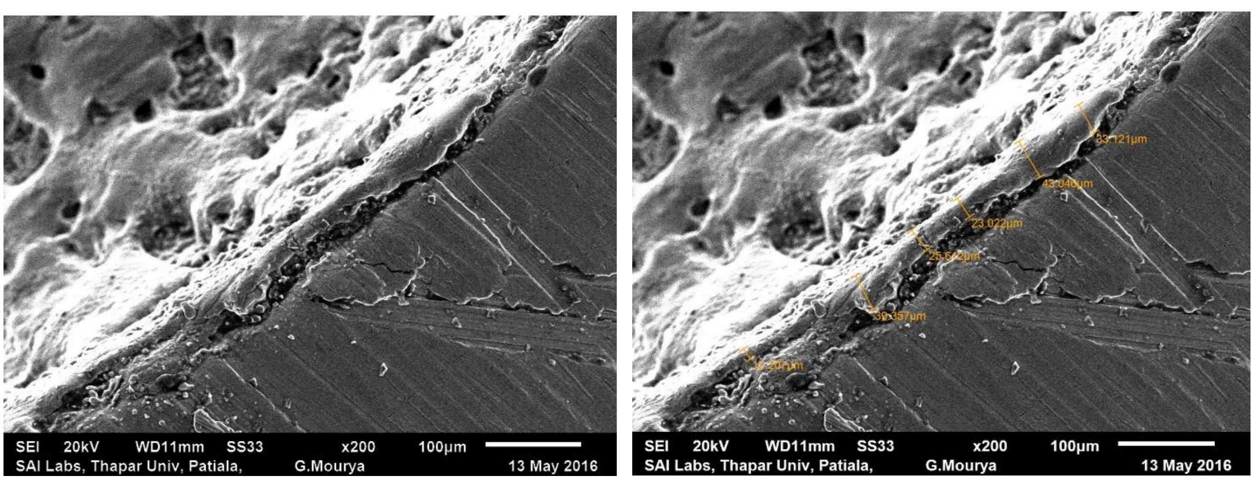


Figure 4.42 SEM micrographs of Ti-6Al-7Nb samples observed RL at peak current=7, pulse on time = 500 mu, pulse off time = 15 mu, Spark gap voltage= 120 V and and Ra= 1.136 µm. [Sai Lab, Thapar University, Patiala]

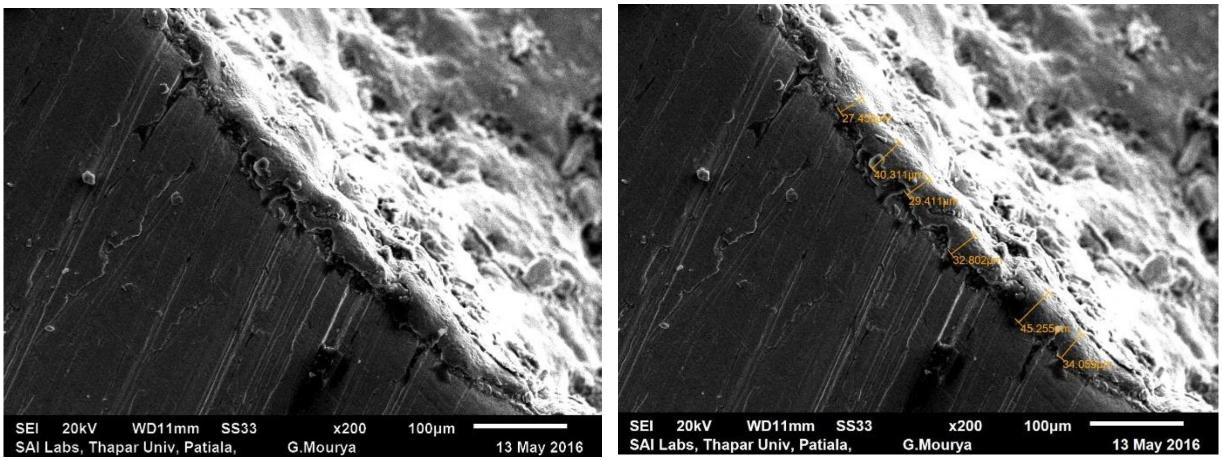


Figure 4.43 SEM micrographs of Ti-6Al-7Nb samples observed RL at peak current=11, pulse on time = 750 mu, pulse off time = 15 mu, Spark gap voltage= 120 V and and Ra= 1.136 µm. [Sai Lab, Thapar University, Patiala]

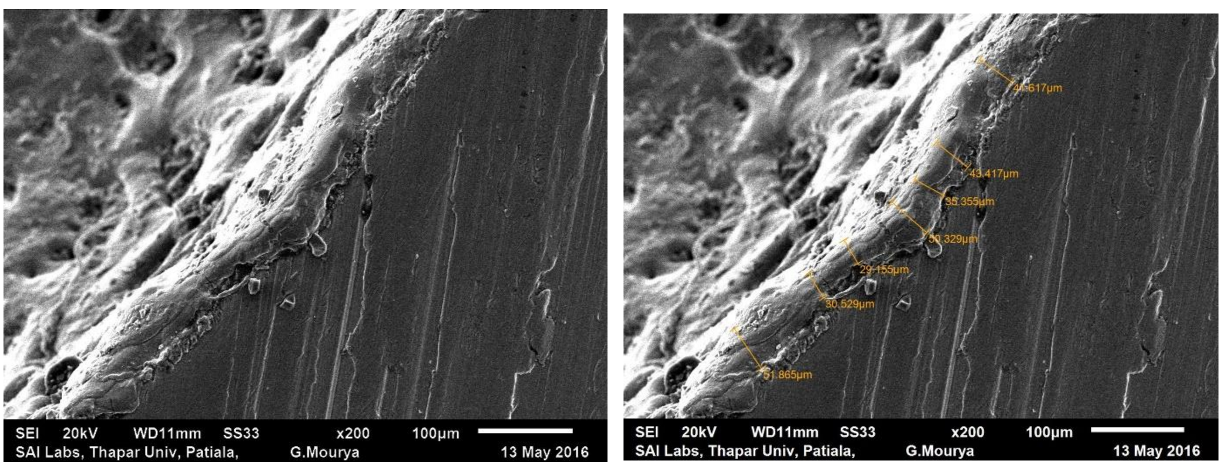
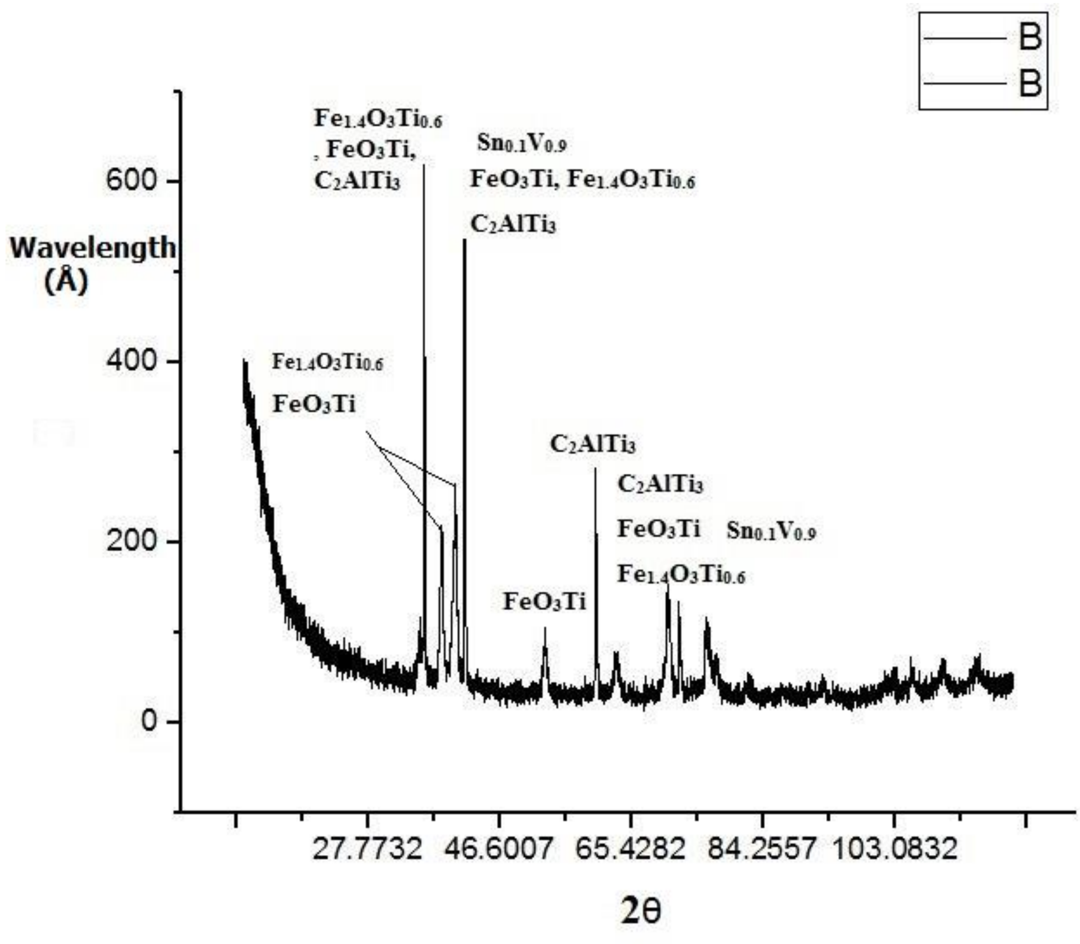


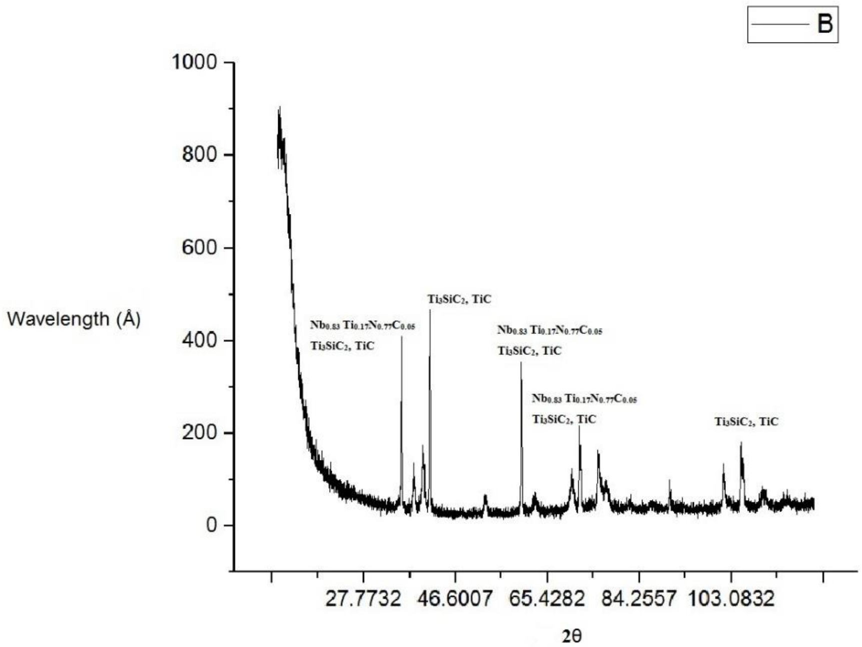
Figure 4.44 SEM micrographs of Ti-6Al-7Nb samples observed RL at peak current=15, pulse on time = 500 mu, pulse off time = 15 mu, Spark gap voltage= 120 V and and Ra= 1.136 µm. [Sai Lab, Thapar University, Patiala]

4.5.4 Results And Discussion On XRD analysis

XRD analysis confirms the migration of element of tool, element of dielectric fluid, element of foreign particles on the surface of base metal or work-piece. And they were observed in free form or in compounds form such as **$Fe_{1.4}O_3Ti_{0.6}$, C_2AlTi_3, FeO_3Ti, $Sn_{0.1}V_{0.9}$, $Nb_{0.83}Ti_{0.17}N_{0.77}C_{0.05}$, Ti_3SiC_2, TiC, $Ti_{5.73}C_{3.72}$, $Nb_{0.83}Ti_{0.17}N_{0.77}C_{0.05}$, NbO_4Ti, O_4TaTi, $Al_2NiOTi3$, $Fe_{2.18}O_4Ti_{0.42}$** as shown in figure 4.45. Phase were identified in the form of peak at the scale of 2Θ angle.

Ti-6Al-7Nb has found its use in medical field as implant devices because of its higher oxidation energy at surface which helps in higher osseo integration, and low wear rate. Use of Die Sink EDM as the processing technique yields the formation of harder compounds of titanium on the surface of the workpiece, which might improve the tribological characteristics of processed titanium.[35] The formation of surface oxide, rutile (TiO2), as observed from the XRD analysis may enable the titanium part to develop optimum wear characteristics [36].





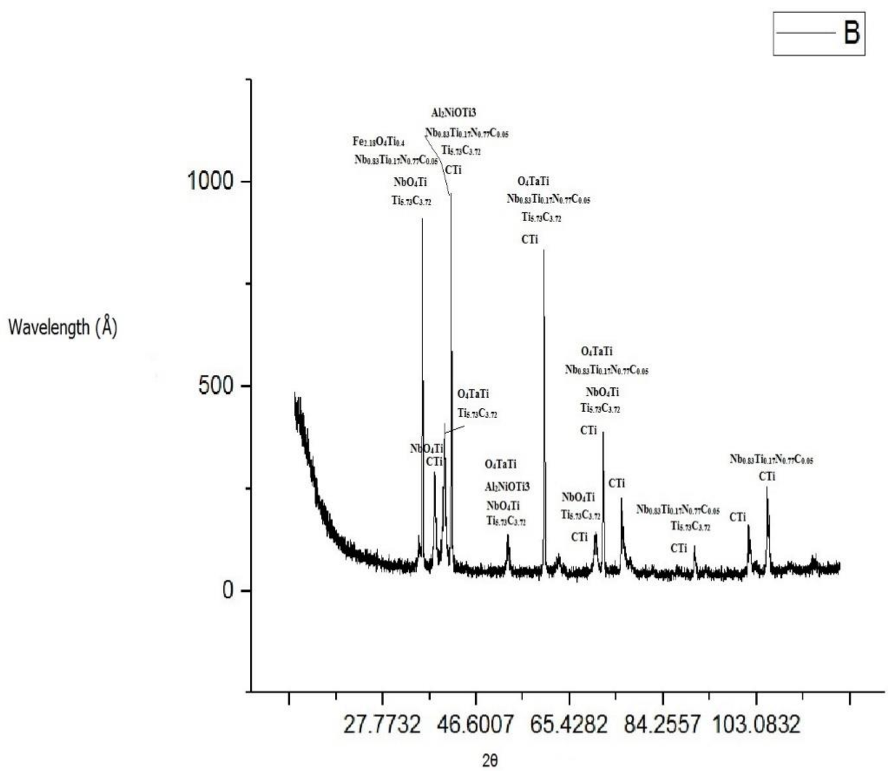


Figure 4.45 XRD Graphs for Ti-6Al-7Nb samples

Chapter 5

Conclusions

In the present study, experimental investigation on Multi-response optimization of process parameters based on response surface methodology and surface integrity of titanium alloy (Ti-6Al-7Nb) after Die Sinking EDM Process was analyzed. There are mainly four significant parameters which were identified, those are, peak current, pulse on time, pulse off time and spark gap voltage, which affect the surface integrity of pure titanium. An experimental plan of the Box–Behnken based on the RSM has been applied to perform the experimental work. The machining evaluation in Die sink EDM has been analyzed and Finally, following conclusions are made

(1) The range of MRR was between 0.81121 mg/min to 1.5145 mg/min during die sinking EDM of Ti-6Al-7Nb samples. Max MRR obtained was obtained when process parameters were selected as peak current = 15A pulse on time = 750 mu pulse off time = 15mu spark gap voltage = 90V .

(2) The range of TWR obtained was between 0.0372 mg/min to 0.1372 mg/min during die sinking EDM of Ti-6Al-7Nb samples. Min TWR was obtained when process parameters combination was chosen as peak current = 7A pulse on time = 500 mu pulse off time = 15mu spark gap voltage = 120V.

(3) The range of SR obtained was between 1.136 µm to 3.912 µm during die sink EDM of Ti-6Al-7Nb samples. Min SR was obtained when process parameters combination was chosen as peak current = 7A pulse on time = 500 mu pulse off time = 15mu spark gap voltage = 120V.

(4) The range of MH obtained was between 1408.39 VH to 1841.35 VH. Max MH was obtained when process parameters were selected as peak current = 15A pulse on time = 500 mu pulse off time = 15mu spark gap voltage = 120V.

(5) ANOVA results showed that developed quadratic models for MRR, TWR, SR, MH were fitted quite well with results of experiments with in 95% confidence level. Pulse on time, peak current, pulse off time and spark gap voltage were found to be most significant parameters for response variables by applying F test in ANOVA. The value of coefficient of regression or R^2 are 0.9718, 0.9773, 0.987and 0.9865 for MRR, TWR, SR, MH respectively.

(6) It was observed that pulse on time, peak current and pulse off time are most responsible factors or process parameters which defines the surface topography which contains shallow craters, deep and wide overlapping craters, poke marks, globules of debris, micro cracks and lumps of debris. Micro cracks were formed because of rapid heating and cooling and pulse on time and peak current are responsible factors for micro cracks.

(7) it was observed that machined surface also have micro ridges which were formed by molten material during machining.

(8) RL was developed in the base metal, it was developed because of high discharge energy and high discharge energy was formed because of high pulse on time, low pulse off time and high pulse on time. RL thickness varies from 12.207 µm to 59.008 µm.

(9) Using XRD machine, it was observed that compound like Ti_3SiC_2, Khamrabaevite (TiC), $Nb_{0.83}$ $Ti_{0.17}N_{0.77}C_{0.05}$, $Ti_{5.73}C_{3.72}$, NbO_4Ti, Titanium(III) tantalum oxide O_4TaTi, $Al_2NiOTi3$, Titanomaghemite $Fe_{2.18}O_4Ti_{0.42}$, Ilmenite $Fe_{1.4}O_3Ti_{0.6}$, C_2AlTi_3, Ilmenite FeO_3Ti were formed

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