An Investigation on Machinability Characteristics of Inconel 718 Superalloy Using Different Cryogenic Tools in Electrical Discharge Machining

DISSERTATION 2

Submitted in Partial Fulfilment of the

Requirement for Award of the Degree

Of

MASTER OF TECHNOLOGY

In

MECHANICAL ENGINEERING

By

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CERTIFICATE

I hereby certify that the work which is being presented in the Capstone Dissertation entitled **"An Investigation of Machinability of Inconel 718 Superalloy Using Different Cryogenic Tools in Electrical Discharge Machining"** in partial fulfilment of the requirement for the award of degree of **Master of Technology** and submitted in Department of Mechanical Engineering, Lovely Professional University, Punjab is an authentic record of my own work carried out during period of Dissertation under the supervision of **Jaspreet Singh(17676)**, **Assistant Professor**, Department of Mechanical Engineering, Lovely Professional University, Punjab.

The matter presented in this dissertation has not been submitted by me anywhere for the award of any other degree or to any other institute. .

Date: 27-04-2015 **(Pradeep Joshi)**

This is to certify that the above statement made by the candidate is correct to best of my knowledge.

Date: 27-04-2015 **(Jaspreet Singh)**

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List of Abbreviations and Nomenclatures

EDM	**Electrical Discharge Machining**
W/P	**Workpiece**
SCT	**Shallow cryogenic treatment**
DCT	**Deep cryogenic treatment**
T_{on}	**Pulse on-time**
T_{off}	**Pulse off-time**
MRR	**Material Removal Rate**
TWR	**Tool wear rate**
SR	**Surface Roughness**
RSM	**Response Surface Methodology**
Cu	**Copper**
Br	**Brass**
Gr	**Graphite**
ANOVA	**Analysis of Variance**
DOE	**Design of Experiment**
Df	**Degree of Freedom**
µs	**Micro-sec**
µm	**Micro-meter**

Table of Contents

1.1 PRODUCTION PROCESS

The Production process is used to produce, create something from the given input to some desired useful output. The process mainly takes place in three parts as shown in figure below:

The three steps are as follows:

1. Input raw material
2. Transformation process
3. Final desired product

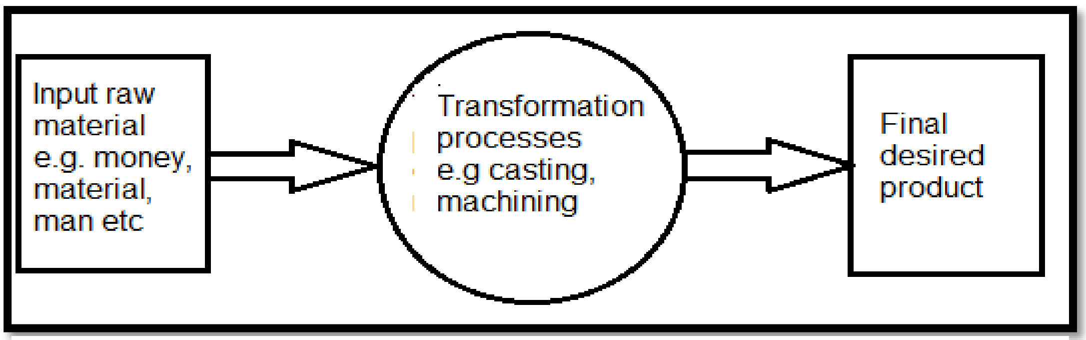

Figure 1 Production process

1.1.1Input raw material: The term Raw material is used to denote material is in an unprocessed or minimally processed state and is the basic material from which goods; finished products or intermediate materials are manufactured or made.

1.1.2 Transformation processes: In transformation process one or more inputs are taken and then some processes have been done on to transform it and add some value to them and provides the outputs. These operations are called manufacturing processes.

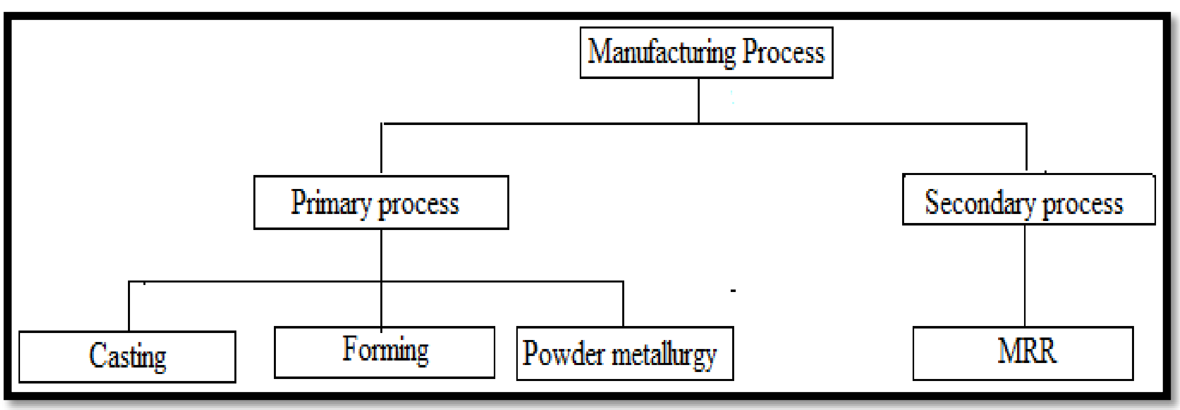

Figure 2 Transformation process

Manufacturing processes are further divided into two more categories:

1. **Primary Processes:** The primary processes provide basic size and shape to the input material as per the given design conditions. The examples of Primary process are Forming, powder metallurgy and casting etc.
2. **Secondary processes:** Secondary processes are the processes that are performed after the primary process. The secondary processes provide final shape and size to the primary processed specimen by controlling its dimension, surface characteristics etc. The example of the secondary process is material removal processes.

Material removal processes are further classified as follows:

i) Conventional processes ii) Non- Conventional processes

1.1.3 Final Output: The product produced by the transformation process which is our requirement is the final output.

INPUT	TRANSFOMATION PROCESS	OUTPUTS
Materials	Location	Product
Peoples	Storage	Service
Equipment	Exchange	

Table 1-1 Production table

1.2 MATERIAL REMOVAL PROCESS

To get the finished surface, shaping operation is performed in which small amount of material is removed from the surface of workpiece. For different operations different material removal techniques are used depending on the requirements. Different processes for material removal are:

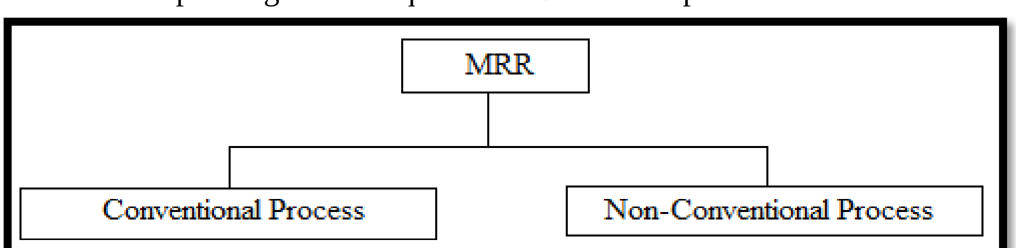

Figure 3 Classification of material removal process

1.2.1 Conventional machining: In this processes materials are removed in the form of chips and there is direct contact between the tool and the workpiece. The type of chip depends up on the material, like may be brittle or ductile it may be continuous or discontinuous. Fragile, delicate materials cannot be machined here because of the stresses on the work piece are very high in this case. As well in this case workpiece should not be much harder than tool and much harder workpiece cannot be machined here. Examples are Drilling, Milling, Turning, Boring and Shaping etc.

1.2.2 Non- conventional machining: Due to some drawback of the convectional machining and for machining very hard, tough, intricate shape, delicate and fragile materials future advanced techniques have been discovered. In this case different other forms of energies other than mechanical energy are used to remove metal and the debris produced is small in shape and size. In non-conventional machining chips are not produced, as tool and workpiece are not in direct contact. This type of machining process is divided further into different types as shown below, depending on the energies of different type used for machining:

(i) Mechanical process
(ii) Electrochemical process
(iii) Electro-thermal process
(iv) Chemical process

Mechanical Process	AJM USM WJM AWJM
Electochemical Process	ECM EJD ECG
Electro-thermal Process	EBM EDM LBM
Chemical Process	CHM PCM

Figure 4 Classification of non-conventional machining

1.2.2.1 Mechanical process: In mechanical processes the metal is removed by either the mechanism of simple shear or by a mechanism of erosion. In erosion mechanism the metal removal take place by high velocity that are used as transfer media and the source of energy is either a hydraulic pressure or pneumatic pressure. It includes water jet machining process, abrasive jet machining process and ultrasonic machine process etc.

1.2.2.2 Electro chemical Processes: By ion displacement mechanism, removal of metal takes place in Electro chemical process. The source of energy required is the high current and the transfer media is electrolyte. The examples of electro chemical processes are electro chemical grinding process, electro chemical machining process etc.

1.2.2.3 Electro thermal Process: Any process which uses an electric current to generate heat by utilizing resistance and arcs to achieve temperatures higher than can be obtained by combustion methods. Here the material removal from the workpiece is occurred by the melting of metal or the vaporization of metal form the small area subjected for process. The types of energies used for electro thermal process are ionized material, high voltage and amplified light. Examples of ETP are ion beam machining process, laser beam machining process, electric discharge machining process, plasma arc machining. EDM mainly used in the shop floors today, is a thermo electrical material removal process (Zang et al. 2006).

1.2.2.4 Chemical processes: In Chemical processes, on certain portion of workpiece the resistant material whether acidic or alkaline in nature in applied. Then on the remaining area of the workpiece etching is applied that converts the work piece material into dissolved metallic salts and the desired amount of material is removed. The examples of chemical processes are chemical machining process and photochemical machining process.

1.3 ELECTRICAL DISCHARGE MACHINING

Electrical Discharge Machining (EDM) is a controlled metal-removal process that is used to remove metal by means of electric spark erosion. Electrical discharge machining (EDM) is a non-traditional concept of machining which has been widely used to produce dies and moulds (Abbas et al., 2007). The shape of the finished work surface is same as the shape of the electrode or tool.

For the metal to be removed the high frequency electrical current is applied by pulsating charge through the electrode tool to the workpiece. At a controlled rate the very small pieces of metal from the workpiece is being eroded. The small area of workpiece is being melt and evaporates by the small plasma channel generated by the small spark with high energy density and high temperature around 8,000 - 10,000 .(Abdulkareem et al., 2009).

Electrical discharge machining (EDM) is one of the most extensively used non- conventional material removal process. In this process material is removed by continuous electrical discharges, between the electrode tool and the workpiece job. As there is no direct physical contact between the electrode tool and the workpiece. These are submersed in a dielectric liquid such as kerosene or deionised water (Abbas et al., 2012). The electrical discharge machining processes are mainly used to machine hard metal sand and its alloy aerospace, automobile and also used in die manufacturing and moulds industries.

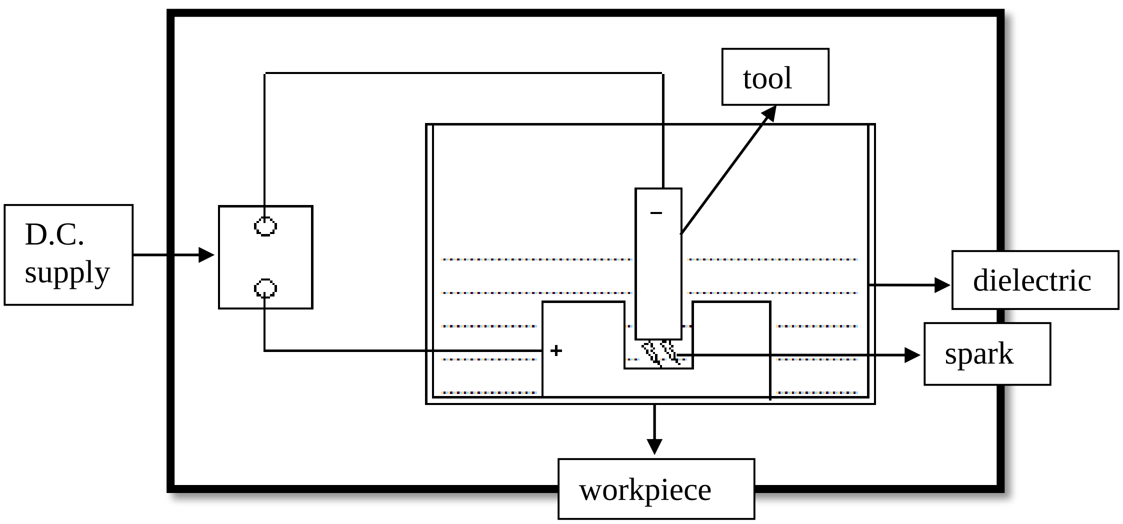

Figure 6 EDM set up

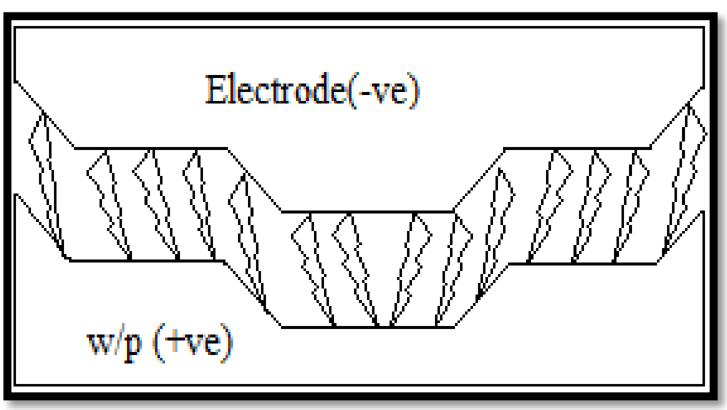

Figure 5 Geometry tool

1.4 HISTORY OF EDM

The erosive effect of electrical discharge on metal is discovered by the English chemist joseph priestly in dates back to 1770. And then after long time in 1943 B.R. and N.I. Lazarenko at the Moscow University exploited the effect of electrical discharge for more beneficial use.

This theory tell us that bulks of electron jumps from a tool electrode and strike the workpiece as a result of which there is rise in the surface temperature which is quit sufficient to melt and expel the molten metal from the surface of the workpiece. A controlled process have been developed to machine metals is by vaporizing the material from the workpiece surface. After this discovery the EDM technology has become the essential process in manufacturing applications such as prototyping, dies and mould making and micro machining etc and developed rapidly. In 1950s a circuit has been developed to automatically find the gap and hold that given gap between the electrode and the workpiece that circuit is a simple servo control circuit with the RC relaxation circuit in which provided the first consistent dependable control of pulse times. In the1980s, for improving the efficiency the CNC EDM was introduced for better machining operation.

1.5 PRINCIPLE OF EDM

The widely accepted principle of material removal in EDM is by the series of electrical discharge that conversion of that electrical energy into thermal energy between the electrode and the workpiece which is dipped in the dielectric medium. (Tsai and Wang, 2001).

EDM is an electro-thermal process i.e. a type of non-conventional process in which removal of material takes places by continuous electric sparks that occurs between workpiece and electrode.

The EDM process can be classified mainly into four groups (Keskin et. al 2006)

I. Workpiece related
II. Electrode related
III. Effective EDM methods
IV. Optimization of EDM parameter

For EDM both the electrode and workpiece should be good conductor of electricity and they are both dipped in dielectric medium (kerosene, EDM oil and water).

The processes of EDM are divided into four stages:

(i) Apply the electrical energy
(ii) Breakdown of the dielectric medium

(iii) Sparking between tool and workpiece

(iv) Removal of metal from the workpiece material (Zang et al., 2006).

When the discharge takes place between two points of the anode and cathode viz. workpiece and electrode, a high amount of high is generated near the zone that melts and evaporates the material in sparking zone. The workpiece is normally made the anode (+ve) because material removal is higher, as the amount of –ve charge ions or electrons are large in number as compared to +ve charge. During Electro discharge machining to avoid the electrolysis, the insulating effect is important of the dielectric.

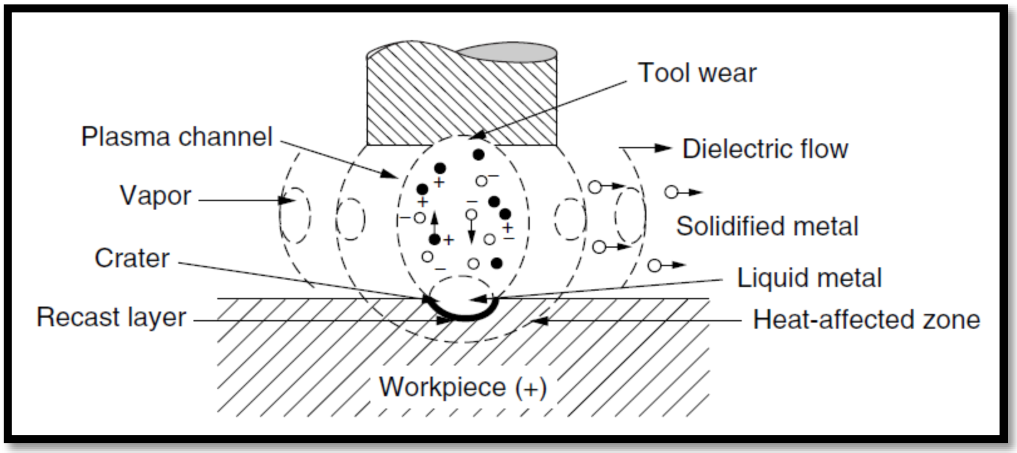

Figure 7 Formation of ions during machining

It is a process of metal removal in which the material removal is take place by an electric spark discharge between electrode and the w/p. depending upon the potential difference applied the gaps of the tool and workpiece maintained the potential difference lies between 50 to 450v, then an electric field is established between the tool and the workpiece. The cathode terminal or the negative terminal of the generator is connected to the electrode and the anode terminal or the positive terminal of the generator is connected to the workpiece. As the electric field is generated between electrode tool and workpiece job it generates the electrostatic force on the electrons of the tool. By this process a very small pieces of the metal is being removed from the workpiece (Weingartner et al. 2012). From the electrode the emission of the electrons take place if the energy of the bonding of electron is very less. This type of emission occurred in the electrons of electrode is known as 'cold emission'. These electrons or we can say cold emitted electrons then moves through dielectric medium towards the workpiece. As these electron gains velocity and the energy, and move towards the workpiece, and collisions would be occurred between the electrons and dielectric molecules. And ionization of dielectric molecules occurs due to this collision. There are also secondary and tertiary collisions. Ionization depends on the energy of the electrons and the ionization energy of dielectric. When the electrons accelerate, more electrons and positive ions get generated due to collisions and produce collision cycle, and this collisions cyclic process in the dielectric medium would increases the concentration of ions and the electrons between the tool and the work piece at the spark gap. The material melts at first and then get evaporates during the discharge (Weingartner et al. 2012). A bulk of electrons will flow from electrode to workpiece and the ions from workpiece to electrode. This motion of the electrons is known as avalanche motion. The movement of these ions and electrons can be seen as electric spark. And the energy of the spark is converted thermal energy from the electrical energy in this way. The kinetic energy of the electrons and ions on impact with the surface of the job and tool respectively would be converted into thermal energy or heat flux. . Spark discharges generate a very small plasma channel having a high energy density and high temperature (Abdulkareem et al., 2012). Such intense localized heat flux leads to extreme instantaneous confined rise in temperature which would be between 8000 to 12,000 °C (Shobert 1983). Such extreme rise in temperature leads to material removal from the workpiece. Material removal mainly occurs due to instant vaporization of the material as well as due to melting of metal. This molten metal is not removed completely but only partially and the erosion of metal from both tool electrodes and the workpiece takes place there. After each discharge capacitor is recharged from the DC source by a resistor, and the spark that occurs is transferred to the next narrowest gap. The duration of machining take place by the charging and discharging of the capacitors take place in a particular manner to machine into the shape of the tool a succession of sparks have been applied on the workpiece which erode the material and we get the shape of the tool on the surface of the workpiece.

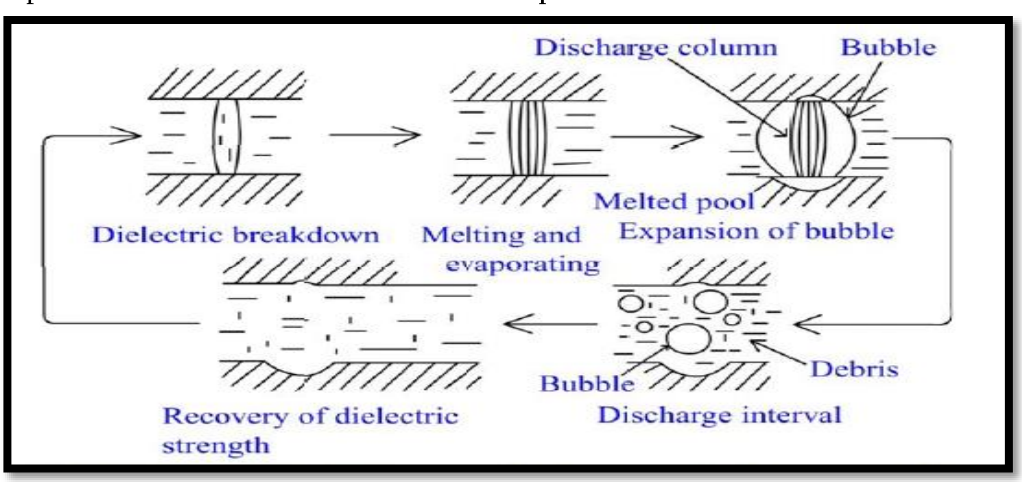

Figure 8 EDM mechanism(NPTEL Module 3 Lecture 9)

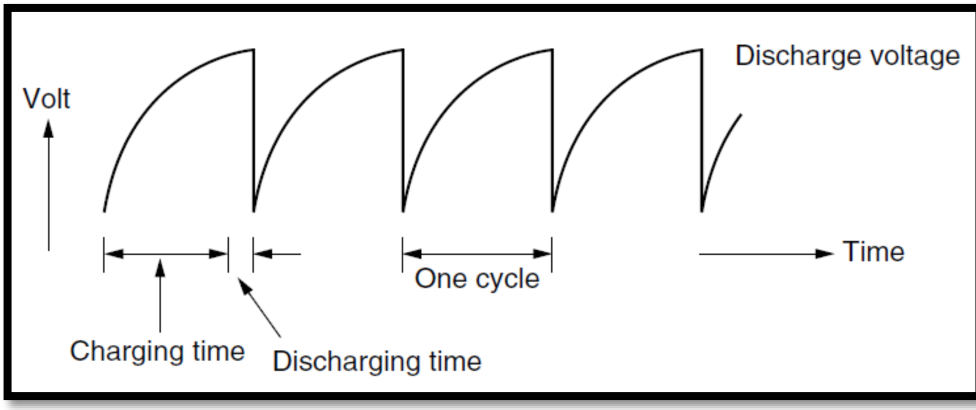

Figure 9 Variation of capacitor voltage with time in RC circuit

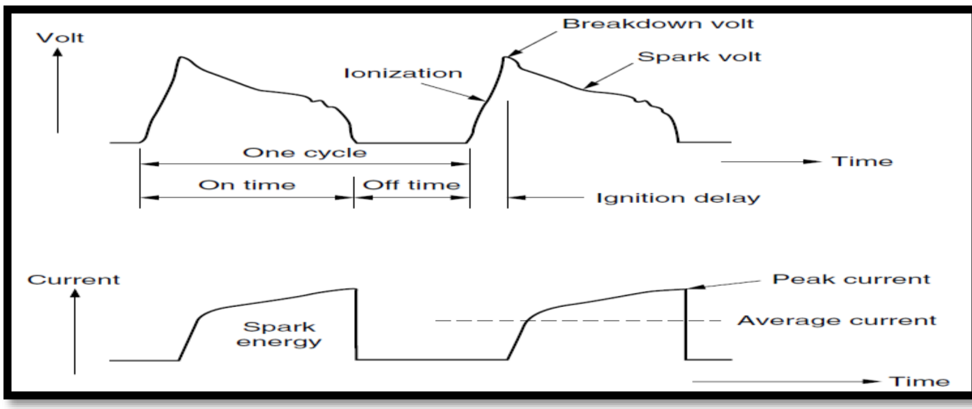

Figure 10 Voltage and current waveform in EDM

1.6 COMPONENTS OF EDM

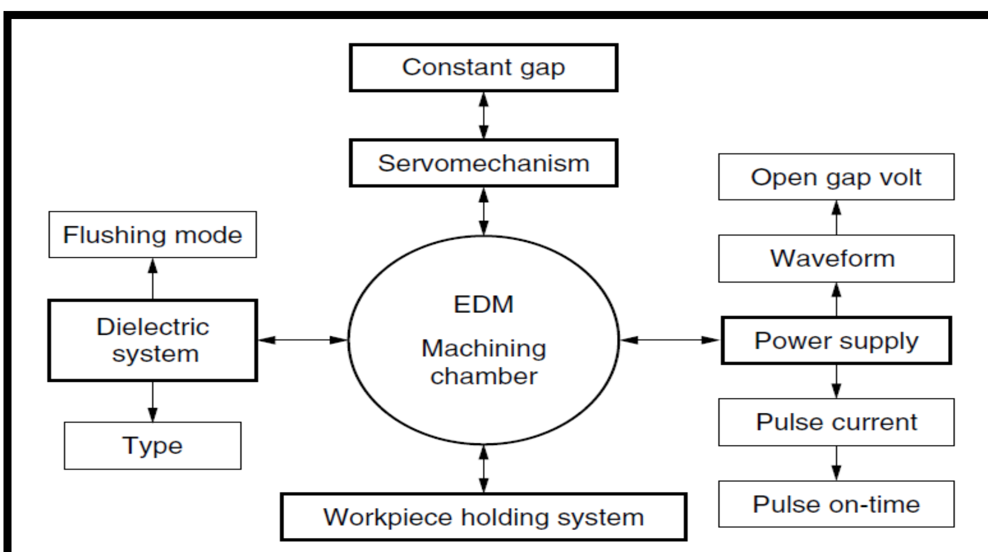

Figure 11 EDM Components

1.7 CLASSIFICATION OF EDM PROCESS

Basically, there are four different types of EDM:

(a) Die-sinking EDM (b)Wire cut EDM (c) Powder mixed EDM

(d) Dry EDM

1.7.a Die Sinking EDM- In Die sinking EDM a impression is generated on workpiece surface which is similar to tool geometry. The wear rate from the surface of tool should be low, so to keep its geometry unaltered. In case of die-sinking EDM, workpiece is made cathode while electrode or tool is made anode, the polarities can be reversed for better operations of machine. In die sinking EDM process, electrode and work piece is immersed in dielectric fluid which is connected to main power supply. When the power supply is switched on a discharge current is set up between the electrode and work piece. When electrode to workpiece gap is very small then dielectric breakdown occurs in the fluid which leads to generation of sparks as result as erosion of work piece occur.

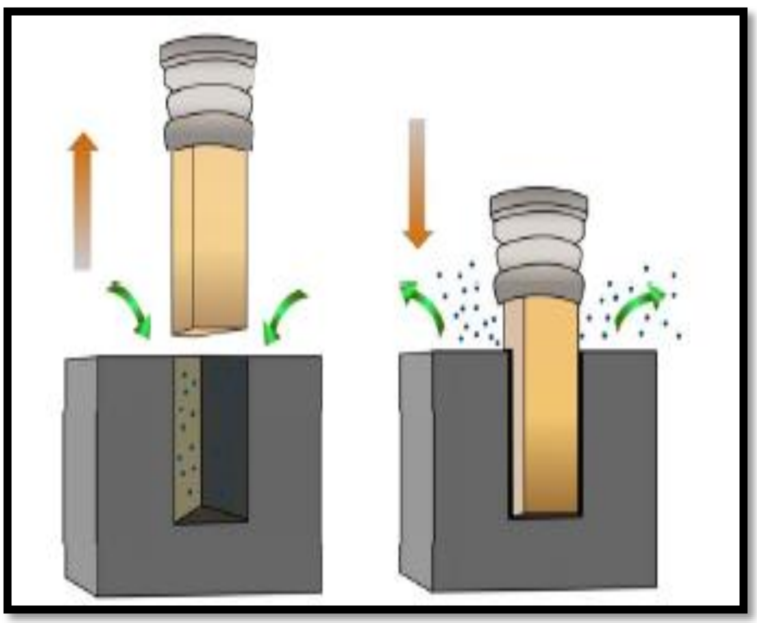

Figure 12 Die sinking EDM

1.7.b Wire EDM- Wire Cut EDM use metal wire as a cutting tool with dielectric fluid such as deionized water. When electric spark is generated, heat is generated which allow the metal wire to cut the material into a desired shape or into a final product. Wire EDM has high surface finish and accuracy. It is used here high precision is required.

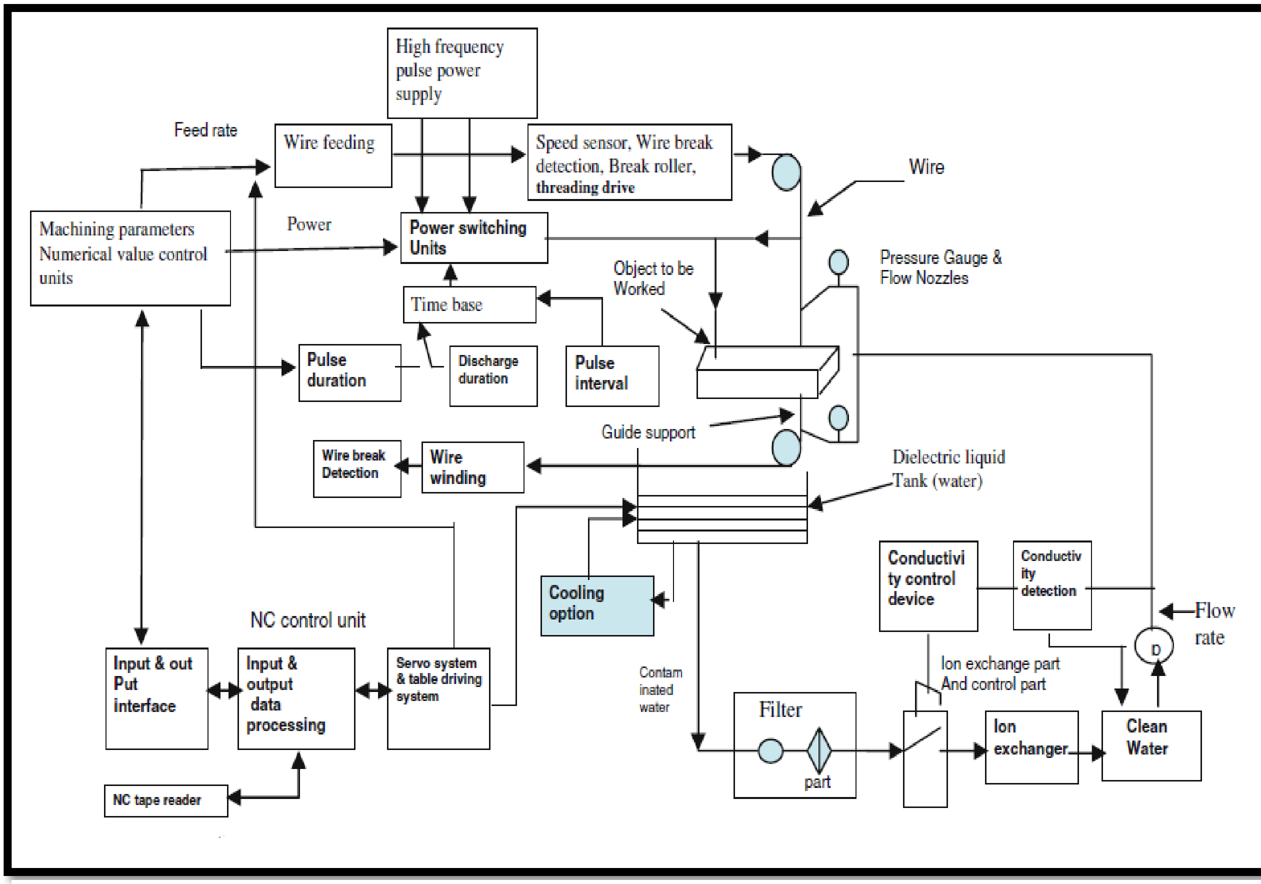

Figure 13 Wire EDM machine (Mahapatra & Patnaik, 2007)

1.7.c Powder mixed EDM- It is similar to die-sinking EDM except a powder that is mixed in dielectric in PEDM. The powder increases the spark gap between the workpiece and decreases the insulating strength of the dielectric fluid and it makes the process stable by increases the MRR and decreases SR. Moreover the surface develops high resistance to abrasion and Corrosion.

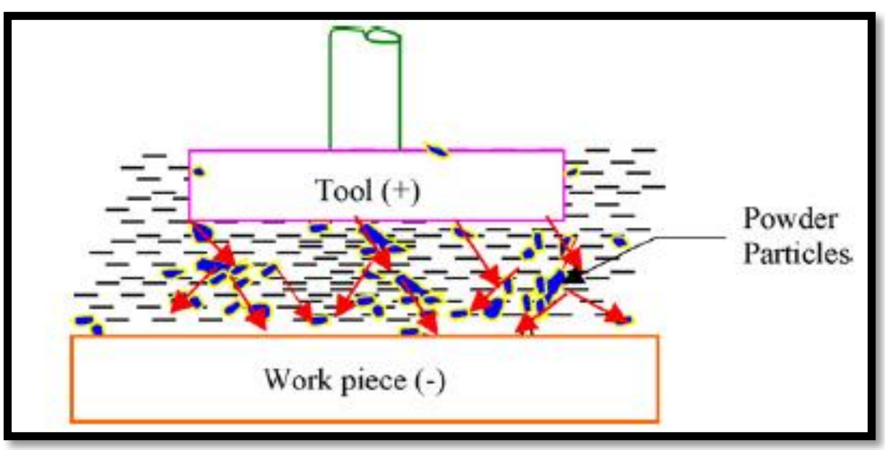

Figure 14 Principle of power mixed EDM (Kensal et.al 2007)

1.7.d Dry EDM - By modifying in the traditional oil EDM the Dry Electric Discharge machining or dry EDM can be made. For modification the liquid dielectric has to replace by gaseous dielectric. The space between tool and workpiece is filled by a liquid namely dielectric medium which plays important roles in EDM process. Generally, the materials of dielectric are oil and other hydrocarbons which they have negative impact on environment and operator when vaporized in hot by sparks. So, in order to overcome this problem, dry EDM process is introduced as a green machining alternative of EDM process (Teimouri and Baseri, 2012).

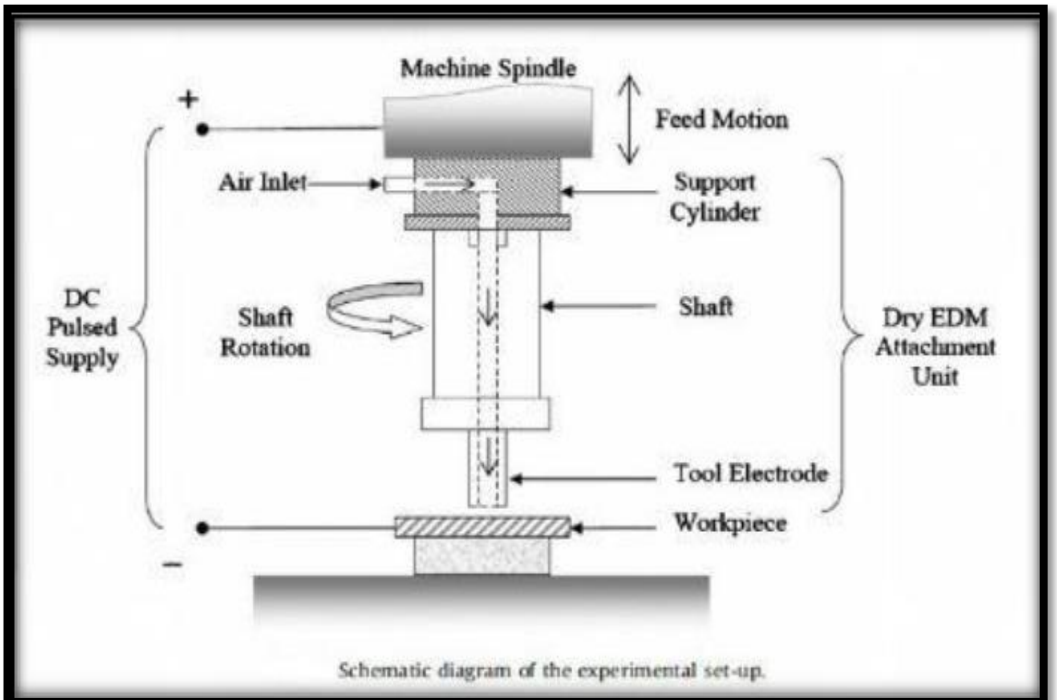

Figure 15 schematic diagram of DEDM (Saha and Choudhury, 2009)

1.8 PROCESS PARAMETER OF EDM

1.8.1 Electrode gap -As the machining action takes place, the gap between tool and the work piece is increased with the help of servo system. For machining process to go good a proper spark gap has to be maintained.

1.8.2 Discharge current - The power supplied to the discharge gap is known as discharge current. The deeper craters are formed by the higher discharge current and it leads to higher pulse energy. This higher current helps to increase the material removal rate and the surface roughness value. Flushing conditions which help in stabilizing the cut can be improved by higher voltage setting.

1.8.3 Polarity - The polarity where the electrode tool is negative and workpiece is positive then that normally known as normal polarity. And in reverse polarity the tool is positive and the workpiece is negative.

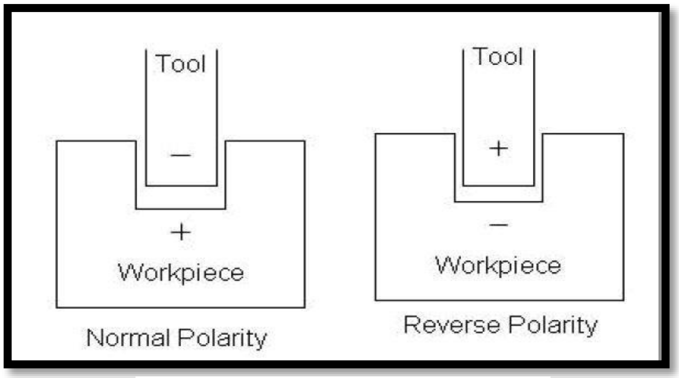

Figure 16 Polarity in EDM

1.8.4 Discharge voltage - The strength of the breakdown of dielectric medium and the spark gap in EDM process is somehow related to the discharge voltage. Discharge voltage through dielectric medium creates ionization path before the current flows.

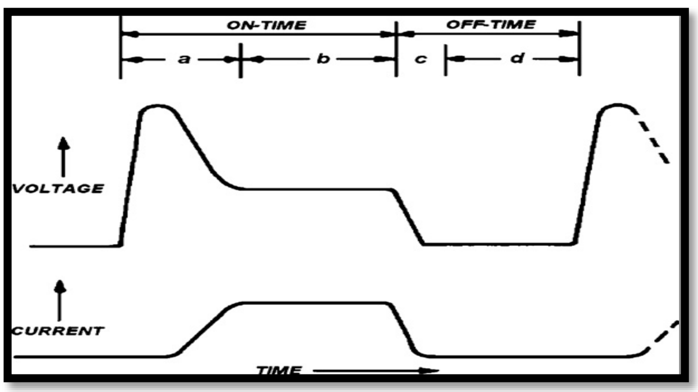

Figure 17 Actual profile of a single EDM pulse (Fuller 1996)

1.8.5 Pulse on-time - The time period of machining is known as the Pulse on time. The amount of energy applied during the pulse on time is directly proportional to the material removal rate. The longer the pulse on-time the more will be the erosion from workpiece resulting in broader and deeper crater and creating rough surface finish.

1.8.6 Pulse off-time - During pulse off time process the power must be switched off and the process must be for some finite time. Short circuits and arcing may occur due to very low value of pulse off time. Re-ionization of dielectric takes place during pulse off time.

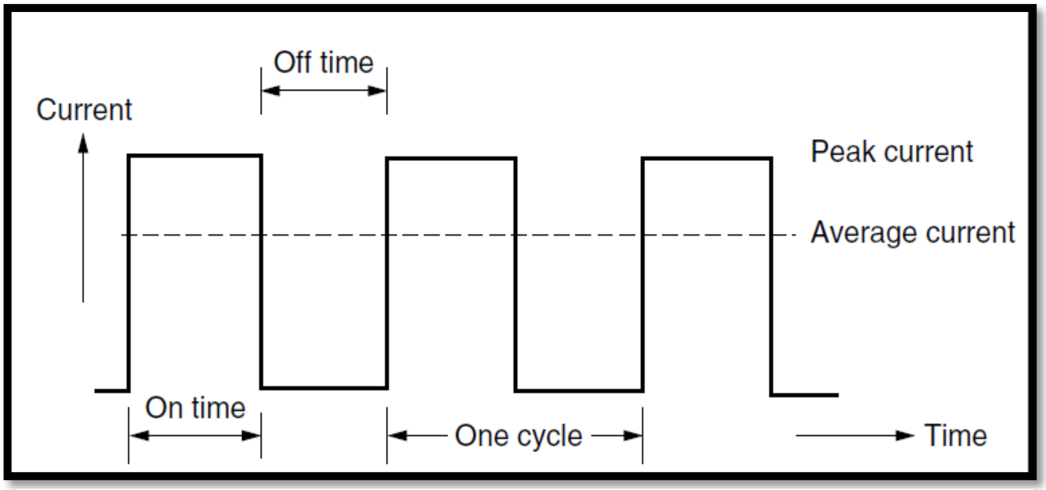

Figure 18 EDM pulse current

1.8.7 Peak current - It is the most important machining parameter used in EDM and is measured in units of amperage it is amount of power used in electrical discharge machining. The peak current is expressed as in each pulse on time the current increases until it reaches a present level it is peak current. Wider craters are formed by the higher peak current value and also rough surface finish. Hence MMR is increased but also decrease the surface finish and increase the tool wear rate.

1.9 ADVANTAGES:

1. In EDM process the materials having electrical conductivity can be machined.
2. By eliminating the heat treatment deformation the hard materials can be easily machined.
3. For the complex profile programming with the arrangement of the X, Y, and Z axes movements machining can be done with the simple electrodes.
4. At faster rate at also at lower cost the more complicated dies and moulds can be made with high accuracy.
5. More and more complex materials can be possible to machine on die sinking machines by modern NC control systems
6. Due to its high automation techniques it can be used for overnight and during the weekends because of the present of the tool and workpiece changer.
7. By using the EDM process the force that is being applied during other mechanical process is absent which make its stress free.
8. The fragile and the thin parts like webs or fins without getting deformed can also be machine in the EDM.

1.10 LIMITATIONS:

1. For machining with the EDM the workpiece as well as the tool should be conductive.
2. There is also a problem to predict the gap between the tool and the workpiece. As the flushing condition and the accuracy depends on it.
3. The material removal rate is quite less in the EDM process.
4. By the combination of the electrical parameters higher material removal rate can be obtained but it is also an difficult process to select the most appropriate parameters.

1.11 CRYOGENIC:

Cryogenics originated from the Greek language Kryo which represents the meaning very cold and genics means to produce. Cryogenics, is the science of study of low temperature and production of at those low temperatures. The cryogenics temperature concerned is not exactly defined but it fall in ranges between temperatures -150° C to -273.15° C which is absolute zero. (Gill and singh,2010) . At these low temperatures many materials changes its many properties. The coldest temperature for cryogenic is not reached up to absolute zero but some fraction of a degree above it. At room temperature the thermal conductivity of the liquid helium gas is several hundred as compared to cu and silver and also it has no viscosity. Cryogenic in practical gives more advantages to some metals. As there are certain metals which on cryogenic treatment as a superconductive materials and loses all its resistance to electric current and if the power is off the also the current will flow through the material these are certain extraordinary properties that we can get through the cryogenic treatment. By the cryogenic heat treatment a very low temperature is attained due to which certain phases like martensite and austenite starts to contract and this contraction is to the high degree. This high degree contraction results in the jumping of the stress

forces carbon atoms which is present in the martensite structure to the defects which is present nearby to it. Or we can say that the decomposition of the martensite structure occurs. Due to this structure contraction and certain other expansion the numbers of defects increases significantly at these low temperatures. For moving carbon atoms the defects like dislocations, twins and some other defect act as appropriate site (Meng et al., 1994).

Through magnetism also the ultra cold temperatures can be produced. When materials are magnetized it will become warm and when demagnetized it become cool. Magnetic refrigerators are being made to reach extremely low temperatures by carefully controlling this process. And also ultra cold attain by compressing the gas and removing the heat by means of ordinary refrigeration and then expanding the gas. Many materials like HHS, carburized steels, polymers, tool steels and composites are the most attractive materials for the area of researchers for the deep cryogenic treatment as these materials gives as the major changing of the properties (Amini et al., 2012).

1.11.1 Cryogenic history

During the Second World War the scientists discovered the metals which is frozen to very low temperature showed the more withstanding with the wear as compared to others. On the basis of the theory in 1966, Scientist Ed Buch with his heat treating industry background founded the commercial cryogenic processing industry in Detroit named cryotech which in the year 1999 combined with 300 other companies and which made it the oldest and the largest cryogenic processing company in the world. By using Cryogenic tempering instead of heat treatment Busch increased the life of metal tool between the 200-400% of the original life. For the treatment of other parts the process has been evolved in 1990.

1.11.2 Cryogenic processing

After heating, quenching and tempering cycle the cryogenic cycle is another extension of the heating process it is not an substitute of the heating process. The cryogenic temperature starts from the room temperature to very low temperature i.e. -273.15° C. The cryogenic processing is followed by the heat tempering cycle with certain procedure. The tempering cycle depends up on the chemical constituents and the materials chemical composition and its thermal history as all the material and alloys do not have some properties The entire cryogenic process takes between 3 to 4 days (yildiz et al).

In cryogenic treatment process the tools is being dipped or immersed into the liquid nitrogen for certain period of time but by directly immersing the tool cases the thermal shocks to be occur in the tool. So the controlled and more effective techniques are used which includes certain things like programmable temperature controllers, thermocouples to monitor the work temperature and a solenoid value to control liquid nitrogen. The cryogenic processing are operated in 3 main stages namely cold down, soaking, warm up and tempering as shown in figure. 1.12. In cool down process the temperature is bought down from room temperature to cryogenic temperature and then in second stage i.e. soaking the tool is dipped in to the liquid nitrogen to certain period of time mainly this stage takes 24-48 hours. In the last stage the tool is removed from the low temperature slowly and the heated to remove thermal shocks this heating process includes certain tempering cycles which depends on the times.

(i)Cooling Stage- In cooling stage the tool is brought down from room temperature to cryogenic temperature slowly with constant time interval. As it has very little effect on the final properties of the tool material. So scientist advised to keep this process rapid to reduce the total processing time as the stress developed during this stage can be removed later by tempering cycle. Thus this rapid process can reduce the time as well as cost of the processing.

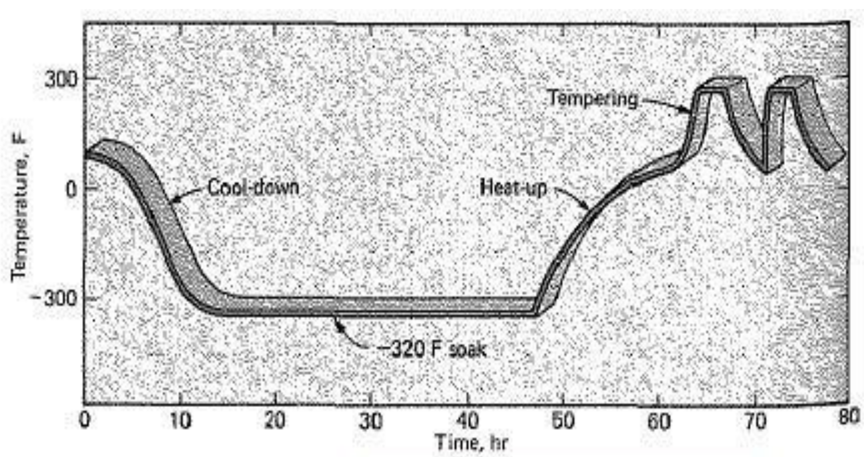

Figure 19 A typical cryogenic treatment cycle (yildiz et al.)

(ii) Soaking Stage - In soaking stage the tool material is being dipped in to the liquid nitrogen for a long period of time. It is the important time duration for the final properties to change in the cryogenic processing. During this soaking time the atoms in the materials dispersed in to new locations. The time duration for the soaking stage is between the 24 hours to 48 hours. The minimum time duration of it is 24 hours for maximum benefits in carbide counts and wear resistance By the longer soaking time higher benefits have been attained for the fine carbide distribution and it also increase the wear resistance for the tool.

(iii)Warming and Tempering Stage - Tempering is usually performed after cryogenic treatment to improve impact resistance of treated materials. It can be carried out as a single, double or triple cycles depending on material characteristics and desired properties. However, for the ultimate effect, no tempering prior to treatment process is recommended and the greatest benefit was derived when cryogenic treatment had been inserted between hardening (quenching) and tempering. Additionally, warming stage should take place slowly and it has been reported that increasing the temperature above 500ºC for the tempering could remove the beneficial effects of cold treatment (yildiz et al).

1.11.3 Application of Cryogenic Treatment

1. Forming tools: Progressive dies, roll form dies etc.
2. Cutting tools: Blades, knives, drill bits etc.
3. Automotive: Brake motors, axel, bearings, ring and pinion etc.
4. Musical: Vacuum tubes, piano wire etc.

In present study literature review is done on the following topics:

1. Die- Sinking EDM
2. Machining of Superalloy
3. Cryogenic treatment of different tools in various machining

2.1 Die-sinking EDM

[1]Sharma et al. [2014] worked on Die sinking EDM machine to study parameters on AISI- 329 using copper and brass rotary electrode during EDM process. In this Author evaluate process performance criteria such as material removal rate and electrode wear rate and taper angle of the hole in AISI 329. Confirmation of the experimental data is done by ANOVA. Authors found that copper electrode improve hole quality and provide good machinability as comparison to brass electrode.

[2]Khan et al.[2014] worked on Die sinking EDM machine to study the surface finish of Ti-5AL-2.5Sn during EDM process. In this Authors evaluate process performance criteria such as surface roughness. Authors found that material of electrode effect surface roughness. Authors also found that at low discharge energy, copper-tungsten electrode gives a excellent surface structure as compared to graphite electrode.

[3]Yoo et al. [2013] experimented on EDM and compared machining capability of commercial WC (tungsten carbide) electrode with that of the home made cermets electrode which was prepared by milling and sintering of Ti(C,N) and (Ti,W)(C,N) along with various carbides, nitrides to drill a micro-hole in a stainless steel thin plate (SS304). During a micro-hole machining process with a Ti-based solid solution carbon nitride electrode, under optimal conditions for the Ti based electrode the EWR was improved by 35.38% and machining time by 45.16% as compared to the EWR for a WC-Co electrode, while for WC-Co electrode, the EWR was improved by 17.0% and the machining time by 18.8% as compared to the EWR for a WC-Co electrode. So the performance of Ti-based solid solution carbon nitride was found better than that of WC-Co for a micro-hole machining EDM process.

[4]Sabur et al. [2013] worked on EDM and investigated using adhesive copper foil as an assisted electrode, the effect of the power that has been supplied on material removal rate and also explored the material removal mechanism on the –ve polarity copper tool in the dielectric medium i.e. kerosene in the Zro2 ceramic. Authors found that pyrolytic carbon layer played the key role for the continuous electric discharge process on the surface of the ceramic which is formed from the carbonic dielectric by the cracked carbon. The factors like the input power, electrode material, workpiece material, tool, dielectric substance, discharge duration and polarity plays an important role in the formation of pyrolytic carbon and also for its stability. The large amount of material is removed by the spalling in the material removal process of Zro2 in EDM process. And with the increase of the power input the melting and vaporization increases by it a little amount of material has been removed. By keeping other parameters constant and by increasing the power input the material removal rate can be increased.

[5] Raghuraman et al.[2013] optimized the techniques used in manufacturing sectors to arrive for the best manufacturing conditions which is an essential need for industries towards manufacturing of quality products at lower cost. And investigated the optimal set of process parameters such as current, pulse ON and OFF time in Electrical Discharge Machining (EDM) process to identify the variations in three performance characteristics such as rate of material removal, tool wear rate, and surface roughness value on the work material for machining Mild Steel IS 2026 using copper electrode. And based on the experiments conducted on L9 orthogonal array, analysis has been carried out using Grey Relational Analysis, a Taguchi method. The optimal parameters combination pulse current at 26A, pulse ON time at 55μs and pulse OFF time at 5μs showed the better results.

[6]Das et al. [2013] investigated about the optimum combination of process parameter in EDM process so that surface roughness reaches a minimum value and the metal removing rate reaches a maximum value on EN31. Authors considered five roughness parameter root mean square roughness, Center line average roughness, skewness and kurtosis along with MRR and mean line peak spacing. To optimize the multi response problems only Taguchi method alone is unable to solve the problem. That is why the multi response characteristics must be converted to a single performance index so Principal components analysis (WPCA) method is used for conversion. The most influencing parameter that significantly affects the roughness and MRR were discharge current.

[7]Raghuraman et al.[2013] optimized the EDM for the important need of the industries for the quality products at the lower costs to get the better manufacturing conditions and the beneficial techniques. Authors investigated on the Mild steel IS2026 material for the workpiece and the copper as a electrode tool with the three output parameters such as electrode wear ratio, material removal rate and the surface roughness finish with the number of input parameters such as discharge current, pulse-on and pulse-off time. By using Grey Relational Analysis which is a Taguchi method analysis were done and the experiments were conducted by using the L9 orthogonal array. By the experiment authors found that there are certain parameter combination which showed the better result such as pulse current at 26A, pulse ON time at 55µs and pulse OFF time at 5µs.

[8]Nikalje et al. [2013] worked on Influence of parameters and optimization of EDM performance measures on MDN 300 steel using Taguchi method. In this Authors evaluated process performance criteria such as material removal rate (MRR), tool wear rate (TWR), relative wear ratio (RWR), and surface roughness (SR) and Selected Parameters which effect EDM performance are Discharge current, pulse on time, and pulse off time. Authors have found that the optimal level of the factors for SR and TWR are same but differs from the optimum levels of the factors for MRR and RWR. Authors found that discharge current, pulse on time, and pulse off time have been found to play significant role in EDM operations. From the result they have found that study of Surface morphological indicates that at higher discharge current and longer pulse on duration gives rougher surface characteristics with more craters, globules of debris, and micro cracks than that of lower discharge current and lower pulse on duration

[9] Singh[2012] worked on Die sinking EDM machine to study the effect of copper chromium and aluminum electrode on EN31. In this Authors evaluate process performance criteria such as material removal rate, electrode wear rate, hardness, depth of cut and over cut. Authors found that brass electrode has a more depth of cut and hardness but copper chromium has a more material removal rate with lower electrode wear.

[10]Azizi et al. [2012] worked on Surface roughness and cutting forces modeling for optimization of machining condition in finish hard turning of AISI 52100 steel. Authors found that surface roughness increases with the increase of feed rate and almost decreases with the increase of workpiece hardness. ANOVA results show that the feed rate, workpiece hardness and cutting speed affect the surface roughness (Ra) by 83.93%, 10.07% and 5.81% in the finish hard turning process, respectively. Authors also found thrust force is at least 1.06 times higher than the tangential cutting force, while the maximum is 2.62 times higher in the range of 46−62 HRC. Authors found optimum value of machining conditions to produce the lowest surface roughness with minimal cutting forces are in the region of: cutting speed, 170 m/min; feed rate, 0.08 mm/rev; depth of cut, 0.1 mm; and workpiece hardness, 56.51 HRC; with estimated surface roughness of 0.309 μm and cutting forces Fa, Fr and Ft of 26.72 N, 134.01 N and 53.92 N, respectively. The average percentage error obtained by confirmation experiments was 19 determined to be 5.89% and 3.06% for surface roughness (Ra) and cutting forces (Fa, Fr and Ft), respectively; which proves the reliability of the equations established.

[11]Pellicer et al. [2011] studied the effect of different process parameters like pulse on time, pulse off time, discharge current and open voltage by using copper electrodes of different geometries on AISI H13 using ANOVA designed experiment on EDM. The output parameters studied were material removal rate, different geometrical and the dimensional micro accuracies and the surface roughness. It was found that by increasing the discharge current the material removal rate increases.. Square and rectangle electrodes were better for both the wear ratios i.e. radial wear ratio and the axial wear ratio.

2.2 Machining of Superalloy

[12]Mahapatra et al. [2014] studied the effect of various parameter during the machining of Inconel 718 by different tools i.e. Graphite, Copper and Brass using EDM to measure MRR and SR. The parameter studied were discharge current, flushing pressure, pulse on-time, duty factor, open circuit voltage and tool material, for the optimization of the result a Box-Behnkin design of response surface methodology is used. The result found that in case of copper and graphite tool, MRR increases monotonically with current but increases slowly with brass tool. The highest MRR is given by graphite tool followed by copper and brass, MRR increase with increase in voltage till a certain point and then decreases. Brass shows good surface finish while Copper and graphite exhibit poor surface finish also increasing the pulse on time decrease the surface quality.

[13]Motorcu et al. [2014] studied the effects of cutting speed (17 m/min 20 m/min, 24 m/min), feed (27 mm/rev, 32mm/rev, 39mm/rev), drill bit angle(980 ,1180, 1420) and cutting tool type were investigated during the drilling of Waspaloy with coated and uncoated solid carbide drills using Taguchi method. The overall mean value of surface roughness was 0.99µm, coated drill bit provide lower surface roughness compared to uncoated, also. Surface roughness increasing with increase cutting speed, drill bit angle and with increasing tool wear. Drill bit angle was found to be the most effective parameter on surface roughness followed by feed rate viz. 15%, cutting speed viz. 14.45% and cutting tool viz. 13.51%. There was no wear found in uncoated tool while chipping and flank wear was found in coated tools.

[14] Laxman et al. [2014] studied the effect of various parameters such as peak current, pulse off time, tool lift and pulse on-time during machining of Inconel 718 with copper electrode using EDM to measure MRR and TWR by Grey relational analysis. It was found that by the proper optimization both the TWR and MRR were improved. The MRR increases from 3.9mg/min to 7.7 mg/min and TWR decreases from 0.3 mg/min to 0.2 mg/min.

[15]Mohanty et al.(2014) used MOSCO algorithm during machining on Inconel 718 in EDM to calculate MRR and surface quality. The results shows that the value of MRR increases monotonically with increase in current for copper and graphite electrodes but increases slowly with the use of brass electrode, material removal was higher while machining with graphite electrode followed by copper and brass. The investigation shows that discharge current, tool material and pulse-on-time were the important parameters during the machining operation.

[16]Baghlani et al.[2013] investigated the effect of spindle speed(355rpm,500rpm,710rpm), number of drilling steps (1*50mm,3*17mm,5*10mm),ultrasonic vibration amplitude(3µm,6µm,10 µm) on surface roughness and machining force during ultrasonic assisted drilling of Inconel 738LC using Taguchi methods keeping a constant feed of 0.05mm/rev. The results shows that increasing vibration amplitude decreases the thrust force and gives better surface roughness, increasing spindle speed increases force and reduce surface roughness.

[17]Thakur et al. (2009) studied the machinability of Inconel 718 using tungsten carbide (K20) tool and the parameter investigated are cutting temperature, cutting pressure, cutting force, surface finish and tool wear. The cutting speed was in between 40-60 m/min, feed 0.05-0.09 mm/rev and the depth of cut 0.5 mm. The result shows that cutting force was in good condition in a speed range of 45-55 m/min but after 60 m/min there is an increase in tool wear rate, it was also found that there was a reduction in specific cutting pressure as the cutting speed increases at constant depth and feed rate. Increasing the feed and speed increases the temperature at tool-chip interface. The feed rate of 0.08 mm/rev and a cutting speed in between 45-55 m/min gives optimum surface roughness. The plastic deformation was found in high amount.

[18]Kuppan et al. [2008] studied the effect of deep hole drilling of Inconel 718 by copper tool (dia 3mm) using EDM. The parameter investigated were electrode speed, pulse on-time, duty-cycle, and peak current and CCD is used for planning of experiment. The results obtained shows that increasing the current increase the MRR. The MRR increases with increase in peak current, electrode rotation and duty-cycle while pulse on-time increases MRR up to 60µs beyond this MRR decreases and also increasing the electrode speed increases the MRR. Results also shows that increase in current and pulse on-time increases average surface roughness while it decreases with increasing duty cycle and electrode rotational speed.

[19]Nalbant et al. [2006] studied the effect on cutting force by varying cutting speed and cutting tool geometry. Inconel 718 is machined with 4 different ceramic tools (KYON 2100 SNGN 120712, KYON 4300 SNGN 120712, KYON 2000 RNGN 120712 and KYON 4300 RNGN 120700) at various cutting speeds which are 150 m/min, 200 m/min, 250 m/min, 300 m/min along with depth of 2mm and feed rate of 0.20 rev/min which was kept constant throughout the experimentation. The lowest cutting force was 672N and the highest was 1346N. An increment-decrement relationship is found between cutting speed and cutting force. Increasing the cutting speed by 66.6% (150-250m/min) decreases the cutting force by 14.6 % and increasing the cutting speed by 20% increases the cutting force by 10.4% because high cutting speed of Inconel leads to plastic deformation, crater, notch wear and side surface of tool, the lowest value of cutting force is found at 250m/min. It was also found that increasing tool tip radius increases main cutting force. The cutting force of tool KYON 4300 RNGN 120700 was higher as compared to other three tool produced similar force.

[20]Altin et al. [2006] studied effect of cutting speed on tool life and tool wear during the machining of NBSA Inconel 718. The tools used during the experimentation is whisker reinforced aluminum oxide ceramic tool Al2O3 + SiCw (KYON 4300 SNGN 120712 and KYON 4300 RNGN 120700) and silicon nitride (KYON 2000 RNGN 120700 and 2100 SNGN 720112) based tool having two different geometry (square shape and round shape) and three different ISO qualities with 10% water additive cutting fluid. The cutting speed was taken between 150 m/min to 300 m/min and a constant feed and depth of cut is maintained viz. 0.20 mm/rev and 2 mm. The wear in round type inserts are notch and flank while in square one crater and flank wear are major. The optimum cutting speed deducted from experiment is 250 m/min. At low cutting speed the performance of square was good them round type inserts and at high cutting speed round was better than square type inserts.

[21]Ezugwu et al. [2004] studied the effect of varying coolant pressure on tool performance during machining of Inconel 718 with coated carbide tools at high cutting speed. The cutting speed were 20, 30, 50 m/min along with a feed rate of 0.25 and 0.3 mm/rev and a depth of cut of 2.5-3.0 mm, the coolant supply pressure were110, 150, 203 bar. The parameter observed were tool life, surface roughness and tool wear. The result obtained shows that machining under high coolant pressure increases the tool life by 7 folds, machining at 203 bar coolant pressure produces well segmented chips, at a cutting speed of 20 m/min it was also found that there were an increase in nose wear rate using 203 bar as coolant pressure at both the feed rates. Low value of surface roughness were observed at low feed rate and an increase in feed rate leads to increase in the surface roughness.

2.3 Cryogenic treatment in various material and Cryogenic treatment in EDM

[22]Mohandoss R. performed cryogenic treatment of EN – 19 alloy steel material to improve its mechanical behaviour. The material was deep cryogenic treated at -191℃ for 24hrs. The mechanical behaviour of untreated EN-19, case carburized EN-19 and carburized and cryogenic treated EN – 19 were found by conducting tests such as tensile testing, impact strength and Rockwell hardness. The tensile strength in cryogenic treatment is increased by 22.62% and in carburised it is increased by 7.94% as compared to un-treated material. The hardness in cryogenic treated steel is increased by a amount of 55%. The result also shows that ductile material is converted to brittle material by the application of cryogenic treatment.

[23]Liqing and Yingjie[2013] performed a set of experiments on the EDM with oxygen, nitrogen, argon and compressed air with quenched 45 carbon steel as work material and copper tube the tool. Amongst all these gases, it has observed that maximum MRR i s with the oxygen gas. MRR of oxygen mixed dry EDM was increased greatly as compared to the non oxygen, single gas dry EDM, by no less than 200%. Then further a cryogenic cooling device was set to cool the work piece effectively by using liquid nitrogen coolant contained in a kettle shaped vessel. A copper tube electrode of outer diameter 6.0 mm and inner diameter of 3.0 mm was used with different parameters like pulse off and pulse on time, gap voltage, peak current and compressed air pressure. By increasing the peak current value, the MRR was found to increase as compared to the results for obtained for work piece without cooling. Cryogenically cooled machining marginally improves the SR value. The MRR and SR can be improved for cryogenically cooled workpieces with both positive and negative polarities.

[24]Srivastava and Pandey [2013] had been studied on the electrical discharge machining which is ultrasonic assisted cryogenically cooled on the copper titanium carbide electrode tip which is sintered. The process parameter considered were discharge current, gap voltage, duty cycle, and pulse-on time. Cermet was fabricated having copper content of 75% and titanium carbide content of 25%, by mixing, pressing, and sintering. Analysis has been done to study about the comparison of the convectional cooper electrode for electrical discharge machining which is ultrasonic assisted cryogenically cooled with performance cermet electrode tip which is newly formed From analysis it had been found that duty cycle, pulse on and discharge current time have most significant effect on the electrode wear ratio in UACEDM process and that electrode wear rate increased with increase in discharge current, and for same set of parameters, electrode wear rate was lowered when cermet tool tip was used as compared to Cu tool tip. It had also been analyzed that MRR and SR increase when cermet tooltip was used as compared to Cu tooltip. By examining the machined surface, it was observed that the amount of recast layer formation and surface cracks decreased when machined by cermet tooltip as compared to Cu tooltip.

[25]Singh and singh, [2013] worked on EDM by using cryogenic electrode to increase the MRR and lowering of the TWR by using cryogenic and non-cryogenic electrode with pulse on/off and current as parameter. With the increscent in the pulse on time tool wear rate of copper is decreased in both electrode cryogenic treated copper electrode and non-cryogenic copper electrode. And tool wear rate is increased with increase in pulse off time. Tool wear rate is very less in cryogenic treated copper electrode as compared to non-cryogenic treated electrode.

[26]Srivastava and Pandey [2012] performed a set of experiments on the EDM to study the effect of cooling on copper electrode and M2 grade high speed steel workpiece. Discharge current, duty cycle, gap voltage and pulse on time were the controllable input process parameters on which authors worked. From experimentation, authors have found that with the increase of duty cycle and the discharge current electrode wear rate increases for both EDM and cryogenic EDM processes. The EWR decreases with increase in pulse on time, however, for the same pulse-on time; EWR is higher as discharge current increases. It is observed that the SR increases with the increase in the discharge current up to 6 A, and then it slightly decreases for both the processes. An increase in pulse-on time with increase in discharge current increases the SR in both the processes. The experimental findings for same parameters are that electrode wear ratio and surface roughness as compared to conventional EDM is lower in cryogenically treated EDM. The reduction of tool wear occurred due to the use of liquid nitrogen.

[27] Amini et al. [2012] investigated on the tool steel 1.2080 having diameter of 50 mm about the time duration of the liquid nitrogen applied for the deep cryogenic heat treatment process and studied about the changes occurred in the micro structure, in the distribution of the carbide and in the carbide percentage, hardness and the micro hardness. Authors performed these analyses via the scanning electron microscope, transmission electron microscope, X-ay diffraction and optical microscope. By the deep cryogenic heat treatment there is increase in the percentage of the carbide and the austenite is removed. Due to improvements in the deep cryogenically cooled samples the hardness and the micro hardness is increased. In application durations more than 36 hours, the hardness and the micro hardness is decreased due to the decrease in the carbide percentage in the sample as compared to the uncooled samples In other words we can say that at the 36 hours for the application of liquid nitrogen the hardness, micro hardness and microstructure uniformity and carbide percentage attained its optimum value.

[28]Gill and Singh [2010] investigated on the machining of the Ti6264 alloy in the EDM and studied about deep cryogenic heat treatment effect on the alloy by drilling it with conducted electrolytic copper tool. And also studied about the accuracy of the drilling holes in the alloy and compared the surface roughness finish and the overcut of Ti6246 which is cryogenically cooled with one which is not cryogenically cooled. On both the workpiece total six drilling setups experiments are performed one setup of drilling for both the workpiece are 30 min, 60 min, 90 min, 120 min, 150 min, and 180 min. From experimentation it is found that the deeply cryogenically cooled Ti 6246 alloy improves the machining condition in the electric discharge machining. The improvement that has shown for different drilling times are up to 8.5% for MRR, 34.78% for TWR, and 30.16% for wear ratio.

[29] Lulay K.E. et al. [2002] studied the effect of cryogenic treatment on 7075 Aluminium alloy. Deep Cryogenic is performed on two specimen one for 2hr and other for 48hrs. There was no effect on any property in 2hrs cryogenic treatment specimen. The effect of 48hrs Cryogenic treatment on the Mechanical properties was about 1%. The largest % change was observed in Charpy test which was nearly 12%.

2.4 Gaps in Literature review

Upon the investigation of various previous papers some gaps were found which are illustrated as follows:

- EDM is generally used for ceramics, metals, composites but very few amount of work has done on superalloy.
- Few researchers used cryogenic treatment during the machining process but none of them had tried cryogenic treatment on tool before the machining process.
- Few amount of work had been done on the tool to reduce the tool wear.

Superalloys have become very important for us because of their widespread use in Engineering. Nickel based superalloy (NBSA) are most widely used family of superalloys. Generally divided into three categories (i) Nickel-Copper e.g.; Monel (ii) Nickel-Chromium e.g.; waspaloy, Inconel (iii) nickel-molybdenum–chromium e.g.; Hastelloy. These alloy have better strength-weight ratio, high corrosion and oxidation resistance, high shear strength and creep strength, highly abrasive carbide particle and are high temperature resistant which makes them useful in aerospace, gas turbine and power industry, marine industry, nuclear reactors, steam production places, petrochemical devices and glass industries etc.[30,31,32]. As superalloy are very hard material it is very difficult to machine them using conventional machining process because of tool breakage, Plastic deformation, formation of crater and notch wear for this reason non-conventional machining method are generally used. Inconel 718 is a family of Nickel-chromium superalloy which contains an age-hardening additive known as nibomium which increases its strength and increases its oxidation resistance. Inconel has excellent oxidation resistant up to 1800^0F strength and temperature resistant from -423^0F to 1300^0F. To prevent the wear of the tool cryogenic treatment has been performed on the tools used during machining and their result on tool life is investigated.

In this research NBSL Inconel 718 is machined using EDM by using different cryogenic tools and the results are optimized using D-optimal method of RSM. The cryogenic treatment was performed to reduce the tool wear because later it affects the shape and geometry of tool which will lead wrong impression on the workpiece.

The main objective of the research are as follows -:

1. To study the effect of various machining parameter MRR and TWR.
2. To optimize the parameter for best value of MRR, TWR and SR.
3. To study the effect of cryogenic treatment of tool wear.

5.1 Description of machine

For the experiment a die-sinking Electrical Discharge Machining of model SPARKONIX with servo-head were used. The dielectric used during machining used was EDM oil having specific gravity 0.763 and freezing point of 94^0C. The flushing used were side flushing with a pressure of 0.2kgf/cm^2.

Figure 20 EDM set up

The machine consists of following parts:

1. Job holding device
2. Tool holder
3. Pump, circulation system and dielectric reservoir
4. Servo system
5. CRO
6. Dielectric tank

5.1.1. Job holding device- Job holding device was a magnetic holding base so that the placed job stick to its surface and does not move by flushing jet pressure. However in this case the material was non-magnetic so iron bars are placed on its both side to prevent its motion.

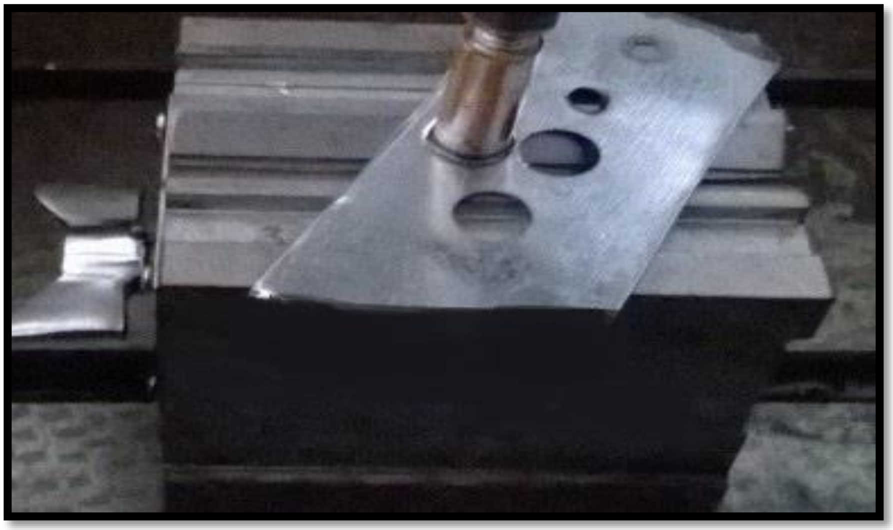

Figure 21 Magnetic Job Holding Device

5.1.2 Tool holder- The tool is mounted on tool holder, the threads of dimension M10*1.5 were made on the tool for attaching it to the tool holder. The tool holder supplies the dielectric inside the tool through the thread hole, to keep it cool during the machining process.

Figure 22 Tool holder

5.1.3 Pump, circulation system and dielectric reservoir- Pump is used to fill the dielectric tank during the machining process and stores it in reservoir after machining. Circulation system circulate and filter the dielectric after machining is over.

Figure 23 Pumps

5.1.4 Servo system- The servo system maintains a predetermined fixed gap between the tool and workpiece.

Figure 24 Servo system

5.1.5 CRO- CRO shows the variation along x, y and z-axis

Figure 25 CRO

5.1.6 Dielectric tank- Dielectric tank contains the dielectric during the machining process. It also carries the job holding device.

Figure 26 Dielectric tank

5.2 Material used

Inconel 718 a NBSA having dimension 50mm*50mm*10mm were used. The hardness of the material was found to be 35HRC. The composition of the metal is given in the table. The tool used were Copper, Graphite and Brass. The tool were having a diameter of 11mm were cryogenic treated before the experiment.

The image of the material is shown below:

Figure 27 Inconel 718 w/p

The chemical composition of Inconel 718 is as follows:

Elements	Original w/p composition (%)	Standard composition (%)
Carbon	0.020	0.08max
Sulphur	0.002	0.015 max
Phosphorous	0.010	0.015 max
Manganese	0.070	0.35 max
Silicon	0.11	0.35 max
Chromium	18.09	17-21 max
Nickel	53.25	50-55 max
Molybdenum	3.14	2.80-3.30 max
Titanium	1.07	0.65-1.15 max
Copper	0.060	0.30 max
Aluminium	0.60	0.20-0.80
Iron	18.15	balance
Cobalt	0.019	1.00 max
Nb+Ta	5.40	4.75-5.60 max
Boron	0.005	0.006 max

Table 2 Material composition

5.3 Tool used

The Experiment was performed in two set with three tools which were Copper, Brass and Graphite. One set of tool was normal tool while the other were cryogenic treated tools.

Figure 28 Brass and Copper tools (Cryogenic and Non-cryogenic)

Figure 30 Non-Cryogenic Graphite tool

Figure 29 Cryogenic Graphite tool

5.4 Parameter used

The parameter selected i.e. input and output were selected depending on the variability of machine and the source available for solving the problem.

5.4.1 Input parameter

The parameter selected for machining were selected on the basis machine capability. The input parameter selected were as follows:

Input Parameter	Parameter Range	Units
Pulse on-time	200-600	μ-sec
Pulse of time	300-700	μ-sec
Discharge current	10-20	Amp
Tool	Copper, Brass, Graphite	

Table 3 Input Parameters

5.4.2 Output parameter

Output parameter	Formula used	units
MRR	$\frac{w_b - w_a}{\rho * t}$	mm^3/min
TWR	$\frac{t_b - t_a}{\rho * t}$	mm^3/min
SR		μ-m

Table 4 Output Parameters

W_b= Weight of material before (gm)

W_a= Weight of material after machining (gm)

T_b= weight of tool before (gm)

T_a=weight of tool after (gm)

ρ = density of material (gm/cm^3)

t= time of machining

Research methodology (RM) is a systematic way to solve a problem. It can also be defined as a science of studying for doing research scientifically. RM deals with the steps adopted by researcher for his problem and also to know the logic behind them. Statistical design helps in the experiment, with the help of which experiment are carried out and proper data is collected for observation.

Advantages of experimental designs are as follows:

- Reduction of number of trials.
- Help to identify the parameter that control and affect the complete process.
- Optimum values of the selected parameter.
- Reduction of error in experiments

In the present work Response surface methodology or RSM has been used to plan the experiments. The idea behind using RSM as to use designed set of experiments for obtaining optimal response. In RSM, D-optimal design method has been used, optimal designs are different classes of experimental designs which are optimal w.r.t statistical criteria. A non-optimal method generally requires high number of experiment for parameter estimation as compared to the optimal ones.

The advantages of optimal design are as follows:

- The cost of experimentation are reduced by optimal design by allowing estimation of statistical model with few experiments.
- Theses design can accommodate different types of factor for e.g. mixture, process and discrete factor.
- Optimization of design even if the design space is constrained.

6.1. Advantage of RSM over Taguchi

- All process parameter can be analyzed in RSM but orthogonal array doesn’t analyze effect of all process parameter.
- RSM provide actual optimal value of a particular parameter but Taguchi merely tells the optimal value for a particular parameter.
- Higher order control factor interaction can be analyzed in RSM however orthogonal array doesn’t.

6.2. Response surface methodology (RSM)

RSM establishes a relation between many explanatory variable and one or few response variable. By a proper experiment design the output parameter can be optimized which is influenced by various input parameter. The cost of expensive analysis method can be reduced by the design optimization using RSM. The relationship among various responses can be shown by the equation:

$$\boldsymbol{y = f(x_1, x_2 \dots \dots \dots \dots . x_k) + \varepsilon}$$

f (x_1,x_2) is known as response surface, the effect of input parameter x_1,x_2…..x_k is shown on output parameter y. The ε shows the error occurred during the measurement of the response. The repossesses obtained can be represented as contour plot or can also be represented in 3-Dimesnional view. Contour curves are constant responses curve along x_i, x_j plane keeping all other variable fixed or contour curve represent a 3-D view to 2-D.

Approximate model function- The relation between independent variable and response variable is generally unknown. Our first step is to find an appropriate relationship. Low-order polymer (first and second order) are more preferable polymers. In applying RSM the mathematical model is fitted on a depend variable which is viewed as a surface. The second degree polynomial has been selected for the development of regression equation related to different quality.

$$\boldsymbol{y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i<j} \sum \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \varepsilon}$$

This shows that y contains square, linear and cross product of X_i.

6.3 D-optimal designs

It leads to more efficient construction of quadric model (Myers and Montgomery, 1995). This design minimizes variance linked along the coefficient approximation of your model. This tends to put many design points along the sides (edges) of your design. Selecting design points P from a larger set of candidature point is the main objective.

Equation can be expressed in matrix notation as - $\mathbf{Y = X * B + \varepsilon}$

X= Matrix of the value of the design variable at plan point, **B=** Vector of tuning parameters

Y= Vector of observation**,** $\boldsymbol{\varepsilon}$ = error vector

B can be calculated by least square method by the equation $\mathbf{B = (X * X^T)^{-1} * X^T * Y}$

According to D-optimal criteria the determinant $|X^T * X|$ maximizes in the experiment by using the best set of points. "D" stands for $|X^T X|$ matrix associated with the model. The D-optimal design gives you the advantage of using irregular shape and making it possible to add extra design point. In computer generated design of experiment D-optimal is the most used.

The table generated through D-optimal design method is shown as below:

Sr. No.	I_p	T_{on}	T_{off}	Tool	MRR	TWR	SR
1	16	300	200	Gr	-	-	-
2	16	500	600	Cu	-	-	-
3	10	500	200	Gr	-	-	-
4	10	300	200	Br	-	-	-
5	20	500	600	Cu	-	-	-
6	10	700	400	Br	-	-	-
7	17	600	200	Br	-	-	-
8	16	500	400	Gr	-	-	-
9	20	700	600	Br	-	-	-
10	20	500	600	Gr	-	-	-
11	20	600	400	Cu	-	-	-
12	10	300	400	Gr	-	-	-
13	20	300	600	Cu	-	-	-
14	20	700	400	Cu	-	-	-
15	10	700	600	Cu	-	-	-
16	14	700	600	Gr	-	-	-
17	12	400	600	Br	-	-	-
18	20	300	400	Br	-	-	-
19	14	700	300	Gr	-	-	-
20	10	700	200	Cu	-	-	-
21	14	400	200	Cu	-	-	-
22	10	500	400	Gr	-	-	-
23	10	300	600	Gr	-	-	-

Table 5 Table for Experimentation

The experiment performed on Inconel 718 superalloy using different cryogenic tools has been performed in two sets:

1- Using Non-Cryogenic treated tools
2- Using Cryogenic treated tools

7.1 Using Non-Cryogenic Treatment

7.1.1 Analysis of MRR

MRR for the Non-cryogenic tools has been calculated and tabulated as shown in the table 6. To collect the data regression analysis has been performed. ANOVA has been performed for the data analysis.

The table for experiment is prepared using Design of Expert software version 9. D-optimal design of RSM has been used. A particular range of I/p parameter was feed in the software to prepare the experiment table.

2FI is recommended as statistically significant for analysis by the fit summary table formed by 'Design Expert' software. The recommended fit summary is shown in **Table 7.** The 2FI model was suggested and chosen for regression modelling. The results of the quadratic model in form of ANOVA are given in **Table 8.**

The model is significant as implied by Model F-value of 33.86. The chance that "Model F-Value" could be large by noise is only a 0.01%. Model terms are significant as the values of "Prob > F" is less than 0.0500. In this case the significant model terms are A, D, AD . Values greater than 0.1000 indicate the model terms are not significant.

The "Pred R-Squared" of 0.8255 is in reasonable agreement with the "Adj R-Squared" of 0.9544. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable (Myers and Montgomery, 1995). Model ratio of 18.191 indicates adequate signal. This model can be used too navigate the design space.

Run	I (Amp)	T_{on}(μs)	T_{off}(μs)	Tool	MRR(mm^3/sec)	TWR(mm^3/sec)	SR(μm)
1	16	300	200	Gr	16.2031	1.9051	12.01
2	16	500	600	Cu	16.6406	3.4151	9.28
3	10	500	200	Gr	9.0152	1.2161	6.78
4	10	300	200	Br	3.1615	0.8951	6.04
5	20	500	600	Cu	24.7265	5.9134	11.67
6	10	700	400	Br	3.545	1.4362	6.78
7	17	600	200	Br	6.1046	2.1532	10.96
8	16	500	400	Gr	18.914	2.1562	11.61
9	20	700	600	Br	9.9146	4.4247	13.78
10	20	500	600	Gr	26.4375	2.9942	13.67
11	20	600	400	Cu	25.9291	6.0161	11.89
12	10	300	400	Gr	6.1251	0.9913	6.03
13	20	300	600	Cu	21.6093	5.1231	10.79
14	20	700	400	Cu	27.5391	7.0707	12.34
15	10	700	600	Cu	10.3162	1.9341	5.8
16	14	700	600	Gr	13.1172	1.8351	10.87
17	12	400	600	Br	4.5046	1.5132	7.46
18	20	300	400	Br	8.5141	3.6134	11.95
19	14	700	300	Gr	12.1172	1.7913	10.58
20	10	700	200	Cu	9.1531	1.4321	6.53
21	14	400	200	Cu	12.4165	2.9121	6.89
22	10	500	400	Gr	10.0156	1.3681	7.67
23	10	300	600	Gr	7.7109	1.0251	6.87

Table 6 Experiment readings before Cryogenic Treatment

Source	Sequential p-value	Adjusted R-squared	Predicted R-squared	
Linear	< 0.0001	0.8580	0.7861	
2FI	0.0168	0.9544	0.8255	Suggested
Quadratic	0.0867	0.9783	0.8728	
Cubic				Aliased

Table 7 Summary for model test fitting

Source	Sum of Squares	Df	Mean Square	F-Value	Prob > F	
Model	1265.61	14	90.40	33.86	< 0.0001	significant
A-Ip	538.09	1	538.09	201.54	< 0.0001	
B-Ton	8.21	1	8.21	3.08	0.1176	
C-Toff	1.72	1	1.72	0.64	0.4457	
D-Electrode	430.92	2	215.46	80.70	<0.0001	
AB	0.32	1	0.32	0.12	0.7389	
AC	3.69	1	3.69	1.38	0.2735	
AD	94.46	2	47.23	17.69	0.0012	
BC	0.29	1	0.29	0.11	0.7519	
BD	23.49	2	11.75	4.40	0.0514	
CD	0.58	2	0.29	0.11	0.8979	
Residual	21.36	8	2.67			
Cor Total	1286.97	222				

Std. Dev.	1.63	R-Squared	0.9834
Mean	13.21	Adj R-Squared	0.9544
C.V.%	12.37	Pred R-Squared	0.8255
PRESS	224.56	Adeq Precision	18.191

Table 8 ANOVA table for MRR before backward elimination

To navigate the design space this model can be used. To improve the model any insignificant model terms needs to be reduced. To fit 2FI model more appropriate, backward elimination process is used to eliminate the non-significant terms. The ANOVA table for the reduced quadratic model is shown in **Table 9 below**

Source	Sum of Squares	Df	Mean Square	F-Value	Prob > F	
Model	1259.54	8	157.44	80.34	< 0.0001	significant
A-Ip	588.83	1	588.83	300.47	< 0.0001	
B-Ton	9.18	1	9.18	4.68	< 0.0001	
D-Electrode	442.63	2	221.32	112.93	0.0002	
AD	105.36	2	52.68	26.88	<0.0001	
BD	21.56	2	10.78	5.50	0.0173	
Residual	27.44	14	1.96			
Cor Total	1286.97	22				
Std. Dev.	1.40		R-Squared		0.9787	
Mean	13.21		Adj R-Squared		0.9665	
C.V.%	10.60		Pred R-Squared		0.9456	
PRESS	70.07		Adeq Precision		27.958	

Table 9 ANOVA table for MRR after backward elimination

The model is significant as implied by Model F-value of 80.34. The chance that "Model F-Value" could be large by noise is only a 0.01%. Model terms are significant as the values of "Prob > F" is less than 0.0500. In this case the significant model terms are A, B, D, AD,BD . Values greater than 0.1000 indicate the model terms are not significant.

The "Pred R-Squared" of 0.9456 is in reasonable agreement with the "Adj R-Squared" of 0.9665. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Model ratio of 27.958 indicates an adequate signal. Thus, the model can be used to navigate the design space.

7.1.1.1 Modeling

After eliminating the non-significant terms, the final response equation for MRR has been obtained by 'Design Expert' software and is given as follows:

Final equation in terms of actual factors for all the three tools i.e. Copper, Brass and Graphite is shown below:

Copper

MRR = -17.00550+ 1.622777 x **Ip** + 0.018662 x **Ton -** 0.012820x **Toff** -2.5656E-004 x **Ip** x **Ton** + 7.46576E-004 x **Ip** x **Toff** + 5.26653E-006 x **Ton** x **Toff**

Graphite

MRR = -5.20842 + 1.44982 x **Ip** -3.80493E-004 x **Ton** -0.010198 x **Toff** – 2.56562E-004 x **Ip** x **Ton** +7.46576E-004 x **Ip** x **Toff** +5.26653E-006 x **Ton** x **Toff**

Brass

MRR = +0.11818 + 0.34881 x **Ip** +2.34834E-003 x **Ton** -0.010568 x **Toff** – 2.56562E-004 x **Ip** x **Ton** +7.46576E-004 x **Ip** x **Toff** +5.26653E-006 x **Ton** x **Toff**

7.1.1.2 Results and discussion

The perturbation plot shown in **Figure 31, 32 and 33** helps to compare the effect of all the factors at a particular point in the design space. One factor was changed while holding all the other factors constant to plot the response over its range. A steep slope for current (A) and pulse on time (B) for the material shows that the response is highly sensitive to that factor however relatively flat lines for pulse off time (C) is less sensitivity to these factors. The factors affecting the response most significantly if more than two factors are present can be easily analysed by the perturbation plot. For Copper and Graphite tool the current line (A) is steep as compared to line B and C while in case of brass the line is not to steep and it is somewhat similar to the other two lines.

7.1.1.3 Effect of current:

It is evident from perturbation plot that MRR is highly sensitive to peak current. MRR tends to increase considerably with increase in peak current for any value of pulse on time as shown in **Figure 34, 35 and 36**. Hence, maximum MRR is obtained at high peak current and high pulse on time. It is because as the pulse current increases it creates strong spark that generate very high temperature and more material is removed from the surface (Pradhan and Biswas, 2008). The trend for variation of MRR along with current is well confirmed with published literature (Pandey and Shan, 2008; Garg *et* al., 2010). For all the three tools, discharge current plays a very important role.

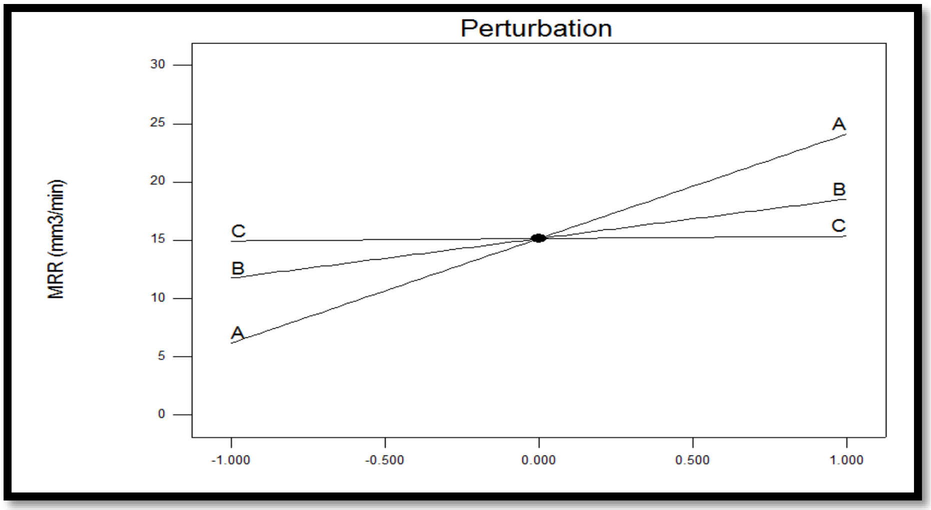

Figure 33 Perturbation plot of MRR with Discharge current for Copper tool

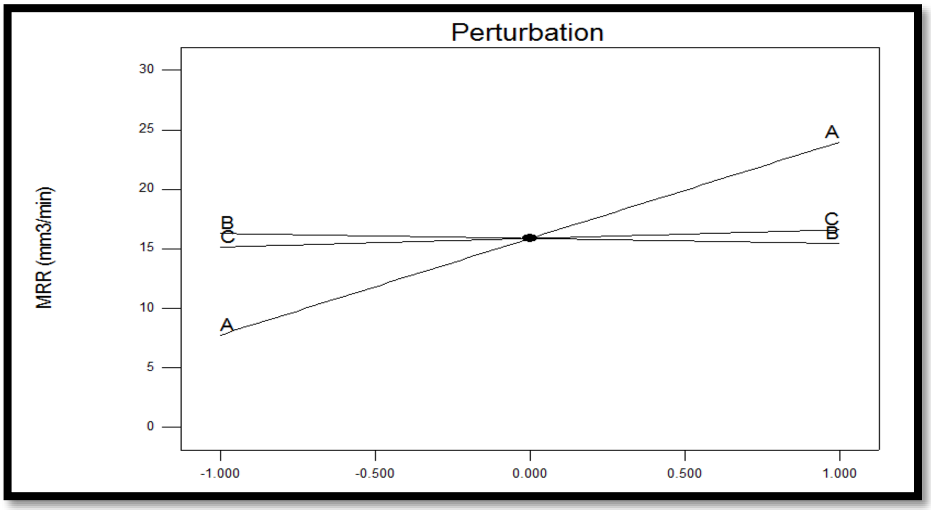

Figure 32 Perturbation plot of MRR with Discharge current for Graphite tool

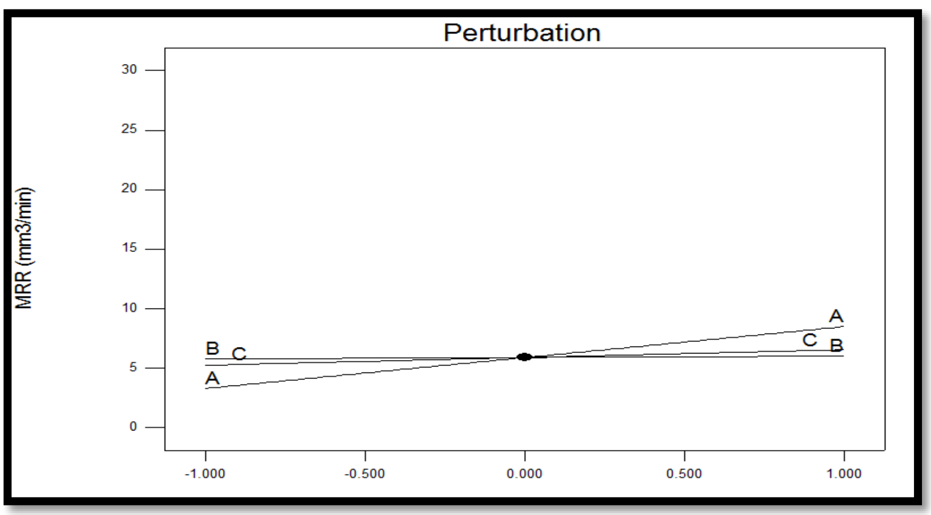

Figure 31 Perturbation plot of MRR with Discharge current for Brass tool

7.1.1.4 Effect of T_{on} and Discharge current on MRR for different tools

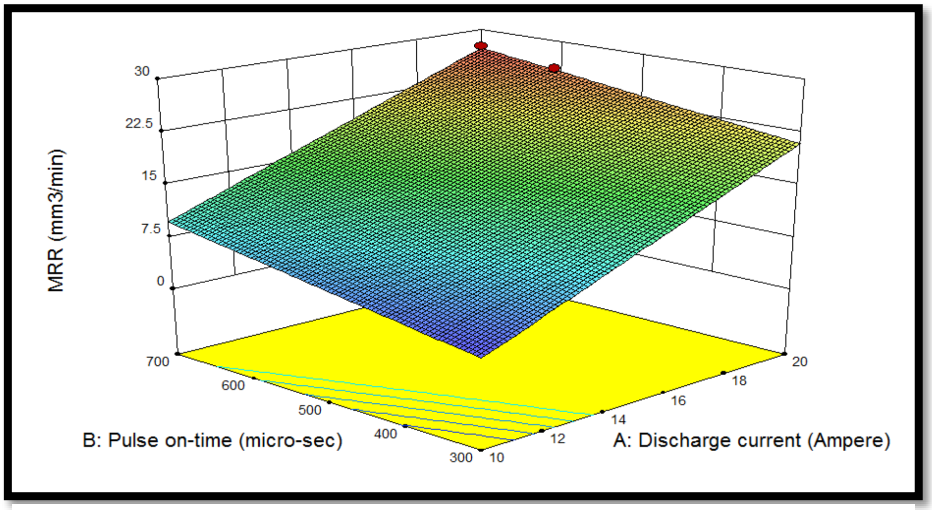

Figure 34 Effect on MRR by Copper Tool

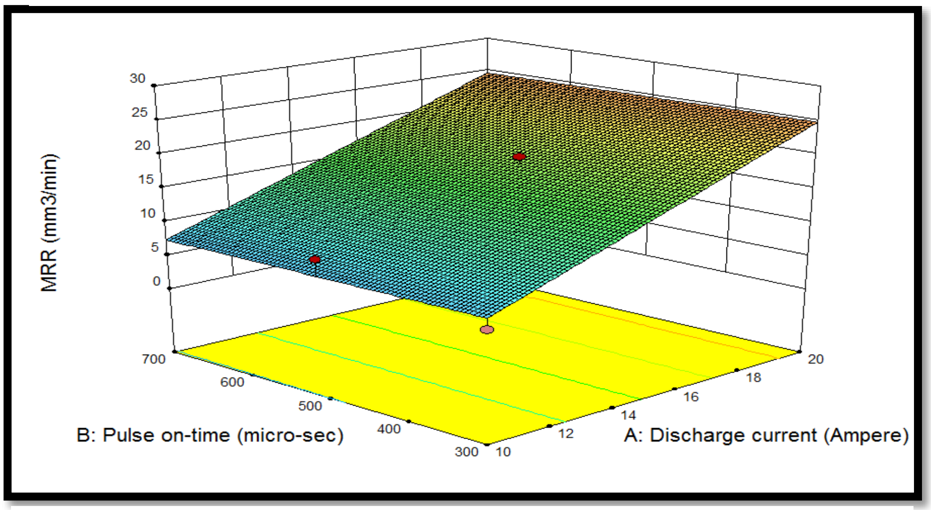

Figure 35 Effect on MRR by Graphite Tool

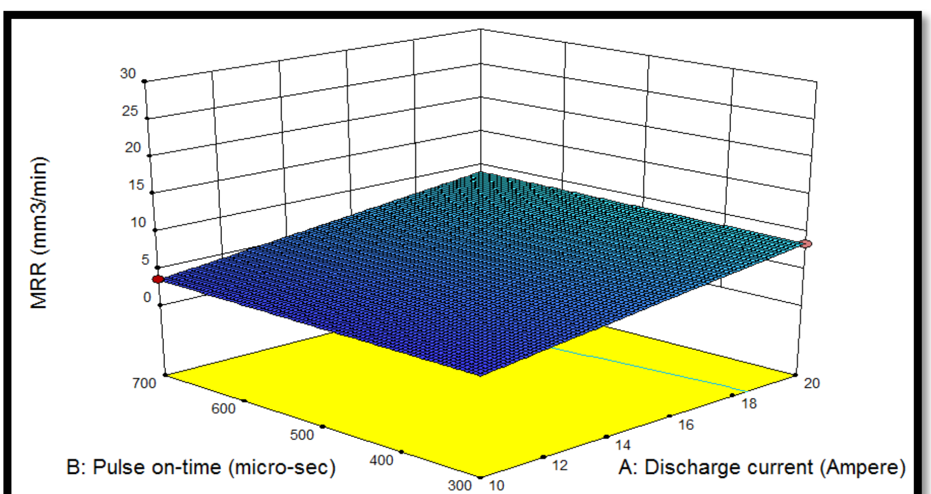

Figure 36 Effect on MRR by Brass Tool

7.1.2 Analysis of Tool Wear

Source	Sequential p-value	Adjusted R-squared	Predicted R-squared	
Linear	< 0.0001	0.8469	0.7858	Suggested
2FI	0.0052	0.9645	0.7574	Suggested
Quadratic	0.2710	0.9723	0.8365	
Cubic				Aliased

Table 10 Summary of model test fitting

Source	Sum of Squares	Df	Mean Square	F-Value	Prob > F	
Model	70.74	14	5.05	43.66	< 0.0001	significant
A-Ip	29.99	1	29.99	259.14	< 0.0001	
B-Ton	1.12	1	1.12	9.67	0.0144	
C-Toff	0.10	1	0.10	0.90	0.3711	
D-Electrode	11.59	2	5.79	50.06	<0.0001	
AB	0.042	1	0.042	0.36	0.5644	
AC	0.091	1	0.091	0.79	0.4004	
AD	4.57	2	2.29	19.76	0.0008	
BC	0.39	1	0.39	3.36	0.1042	
BD	1.01	2	0.50	4.35	0.0526	
CD	0.49	2	0.25	2.12	0.1826	
Residual	0.93	8	0.12			
Cor Total	71.66	22				
Std. Dev.	0.34		R-Squared		0.9871	
Mean	2.74		Adj R-Squared		0.9645	
C.V.%	12.39		Pred R-Squared		0.7574	
PRESS	17.38		Adeq Precision		21.363	

Table 11 ANOVA table for MRR before backward elimination

The 2 factor interaction (2FI) model was suggested and chosen for regression modelling. The results of the 2FI model in form of ANOVA are given in **Table 11**

The model is significant as implied by Model F-value of 22.41. The chance that "Model F-Value" could be large by noise is only a 0.01%. Model terms are significant as the values of "Prob > F" is less than 0.0500. In this case the significant model terms are A, B, C, D, AC, AD, BE, CD. Values greater than 0.1000 indicate the model terms are not significant.

The "Pred R-Squared" of 0.7913 is in reasonable agreement with the "Adj R-Squared" of 0.9240. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable (Myers and Montgomery, 1995). Model ratio of 18.652 indicates adequate signal. This model can be used to navigate the design space. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model. To fit the quadratic model more appropriate, the non-significant terms are eliminated by backward elimination process. The ANOVA table for the reduced 2FI model is shown in **Table 12**

Source	**Sum of Squares**	**Df**	**Mean Square**	**F-Value**	**Prob > F**	
Model	69.73	8	8.72	63.29	< 0.0001	significant
A-Ip	33.31	1	33.31	241.86	< 0.0001	
B-Ton	1.36	1	1.36	9.90	0.0071	
D-Electrode	10.56	2	5.28	38.25	<0.0001	
AD	6.34	2	3.17	23.02	<0.0001	
BD	0.98	2	0.49	3.56	0.0563	
Residual	1.93	14	0.14			
Cor Total	71.66	22				
Std. Dev.	0.37		R-Squared		0.9731	
Mean	2.74		Adj R-Squared		0.9577	
C.V.%	13.52		Pred R-Squared		0.9239	
PRESS	5.45		Adeq Precision		25.230	

Table 12 ANOVA tale for MRR after backward elimination

The model is significant as implied by Model F-value of 63.29. The chance that "Model F-Value" could be large by noise is only a 0.01%. Model terms are significant as the values of "Prob > F" is less than 0.0500. In this case the significant model terms are A, B, Dand AD. Values greater than 0.1000 indicate the model terms are not significant.

The "Pred R-Squared" of 0.9239 is in reasonable agreement with the "Adj R-Squared" of 0.9577. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Model ratio of 25.320 indicates an adequate signal. Thus, the model can be used to navigate the design space.

7.1.2.1 Modeling

After eliminating the non-significant terms, the final response equation for MRR has been obtained by 'Design Expert' software. Final equation in terms of actual factors:

Copper

TWR = -6.02779+ 0.49809x **Ip** + 3.92933E-003 x **Ton**

Graphite

TWR = -0.77313 + 1.16646 x **Ip** +5.26883E-004x **Ton**

Brass

MRR = -2.17409 + 0.26660 x **Ip** +2.34834E+1.1176E-003x **Ton**

7.1.2.2 Results and discussion

The perturbation plot shown in Figure helps to compare the effect of all the factors at a particular point in the design space. One factor was changed while holding all the other factors constant to plot the response over its range. A steep slope for current (A) and pulse on time (B) for the material shows that the response is highly sensitive to that factor however relatively flat lines for pulse off time (C) is less sensitivity to these factors. The factors affecting the response most significantly if more than two factors are present can be easily analysed by the perturbation plot. For Copper tool the current line (A) is steep as compared to line B and C while in case of graphite and brass the line is not to steep and it is somewhat similar to the other two lines.

7.1.2.3 Effect of current:

It is evident from perturbation plot that TWR is highly sensitive to peak current. TWR tends to increase considerably with increase in peak current for any value of pulse on time. This is due to the fact that an increase in discharge current leads to increase of pulse energy. This results in increase in heat energy rate, which is subjected to both of the electrodes. The increased heat energy rate raises the rate of melting and evaporation of electrodes. Thus, the TWR increases with the discharge current. The findings are closely agreed with the previous investigations (Zhang et al., 1997; Sohani et al., 2009).

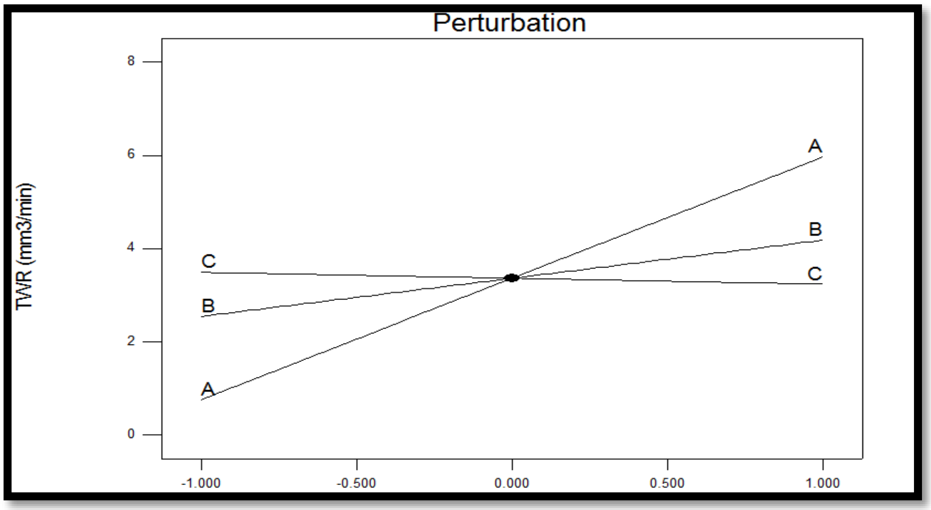

Figure 38 Perturbation plot of TWR with discharge current for copper tool

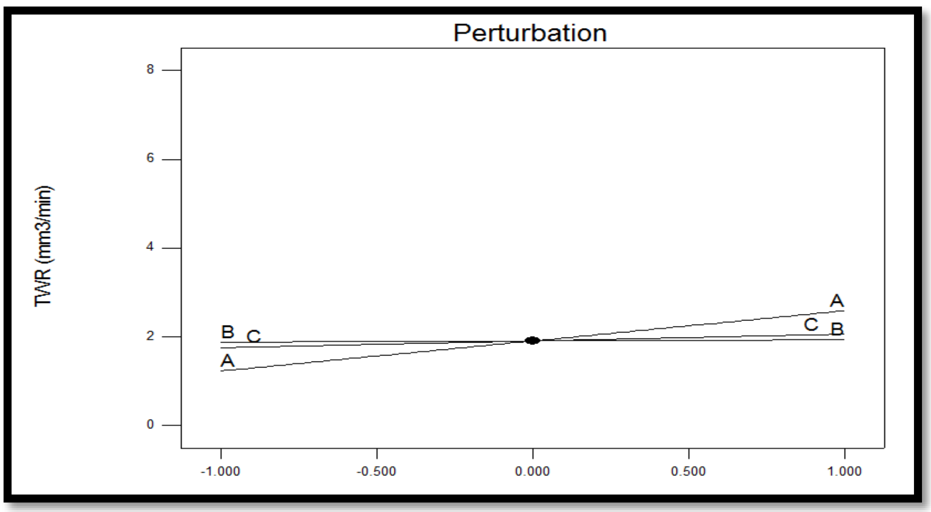

Figure 37 Perturbation plot of TWR with discharge current for Graphite tool

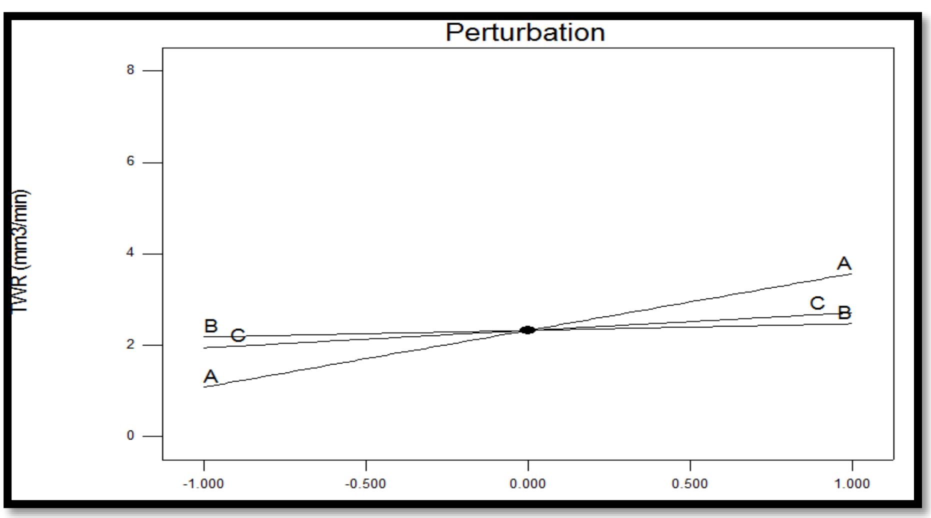

Figure 39 Perturbation plot of TWR with discharge current for Brass tool

7.1.2.4 Effect of T_{on} and Discharge current on TWR for different tools

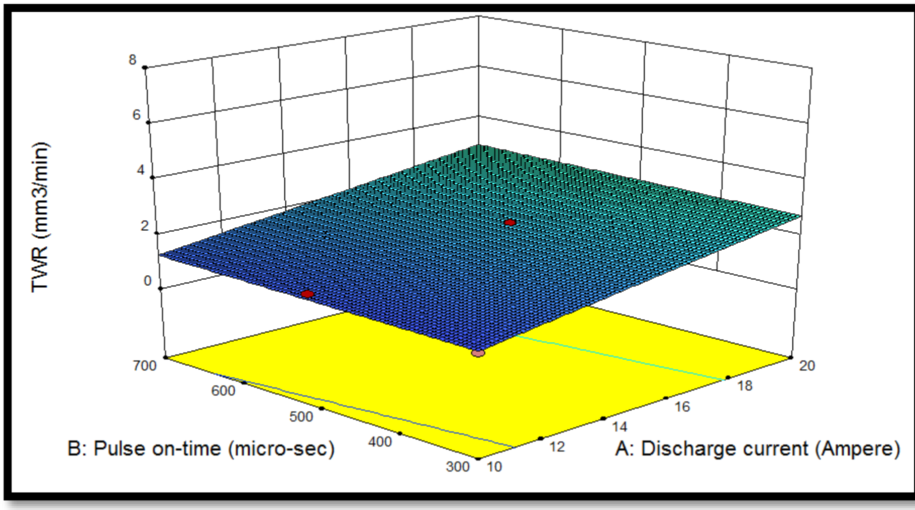

Figure 40 Effect on TWR by Copper Tool

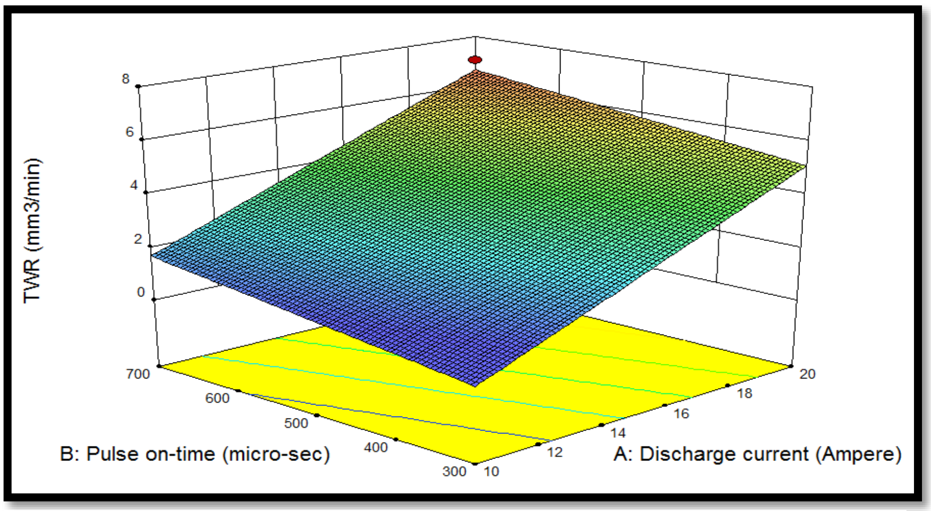

Figure 41 Effect on TWR by Graphite Tool

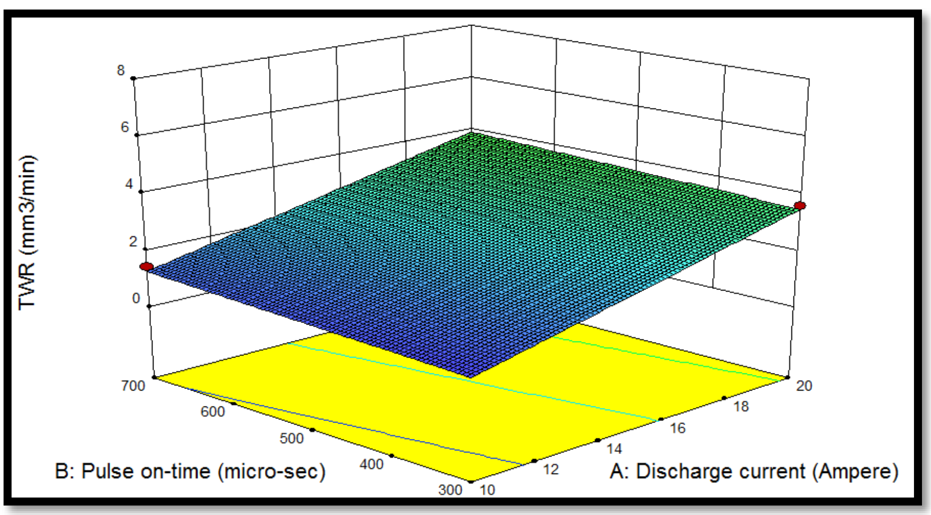

Figure 42 Effect on TWR by Brass Tool

7.1.3 Analysis of SR

Source	Sequential p-value	Adjusted R-squared	Predicted R-squared	
Linear	< 0.0001	0.9604	0.9422	Suggested
2FI	0.9354	0.9391	0.3774	
Quadratic	0.4816	0.9380	-0.1049	
Cubic				Aliased

Table 13 Summary of model test fitting

The model is significant as implied by Model F-value of 107.58. The chance that "Model F-Value" could be large by noise is only a 0.01%. Model terms are significant as the values of "Prob > F" is less than 0.0500. In this case the significant model terms are A, B, D. Values greater than 0.1000 indicate the model terms are not significant if there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The "Pred R-Squared" of 0.9422 is in reasonable agreement with the "Adj R-Squared" of 0.9604 i.e. the difference is less than 0.2."Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable.

Source	Sum of Squares	Df	Mean Square	F-Value	Prob > F	
Model	155.23	5	31.05	107.58	< 0.0001	significant
A-Ip	141.46	1	141.46	490.19	< 0.0001	
B-Ton	5.70	1	5.70	19.75	0.0004	
C-Toff	0.032	1	0.032	0.11	0.7440	
D-Electrode	20.47	2	10.23	35.46	<0.0001	
Residual	4.91	17	0.29			
Cor Total	160.13	22				
Std. Dev.	0.54		R-Squared		0.9694	
Mean	9.49		Adj R-Squared		0.9604	
C.V.%	5.66		Pred R-Squared		0.9422	
PRESS	9.26		Adeq Precision		30.013	

Table 14 ANOVA table for SR

7.1.3.1 Results and discussion

The perturbation plot shown in Figure helps to compare the effect of all the factors at a particular point in the design space. One factor was changed while holding all the other factors constant to plot the response over its range. A steep slope for current (A) and pulse on time (B) for the material shows that the response is highly sensitive to that factor however relatively flat lines for pulse off time (C) is less sensitivity to these factors. The factors affecting the response most

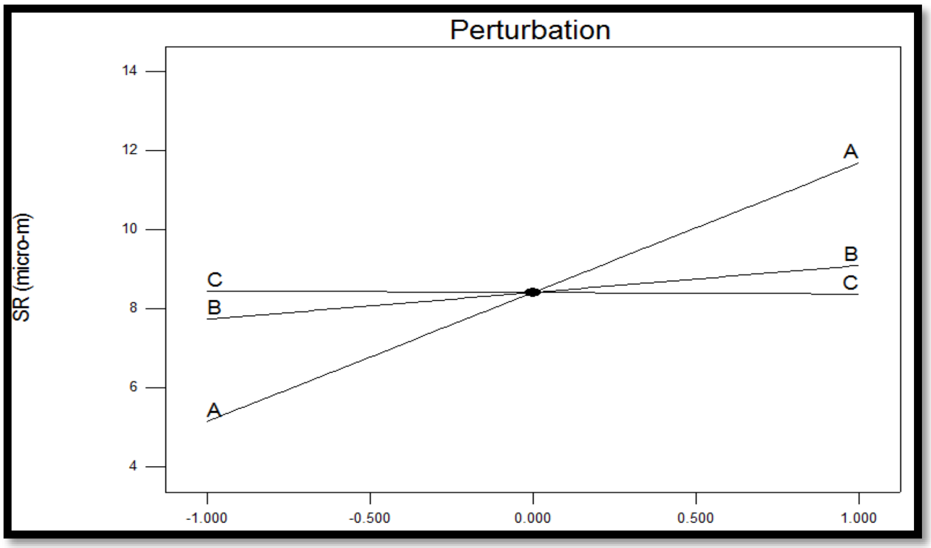

Figure 43 Perturbation plot of SR with discharge current for Copper tool

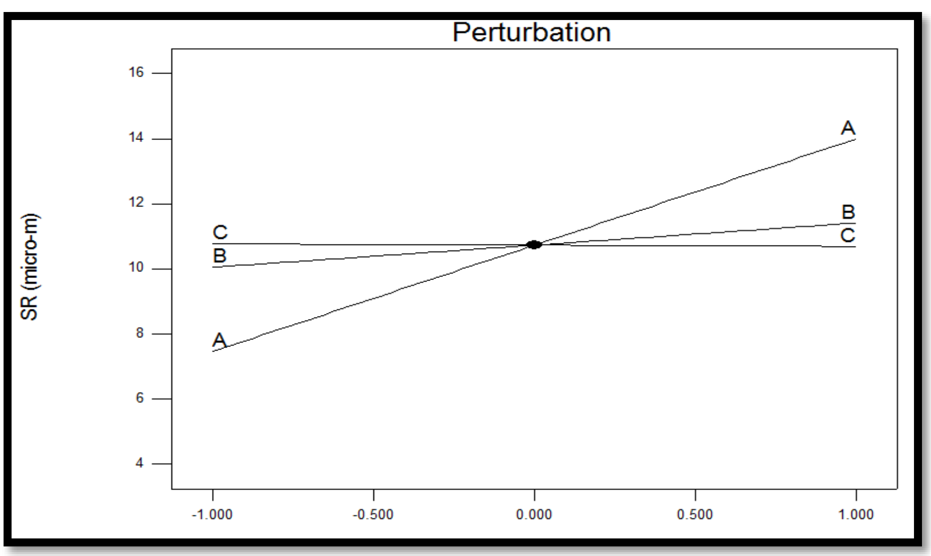

Figure 44 Perturbation plot of SR with discharge current for Graphite tool

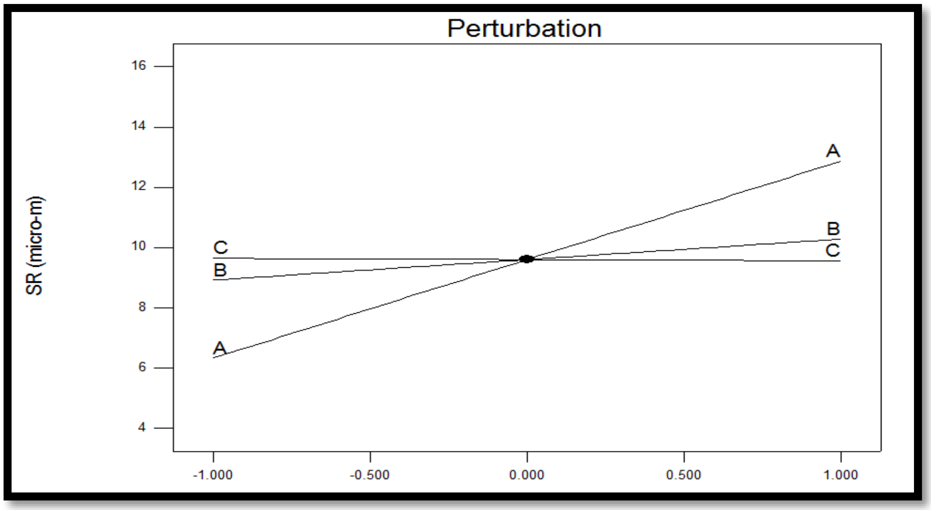

Figure 45 Perturbation plot of SR with discharge current for Brass tool

7.1.3.2 Modeling

After eliminating the non-significant terms, the final response equation for SR has been obtained by 'Design Expert' software. Final equation in terms of actual factors:

Copper

SR = -2.99161+ 0.65037x **Ip** + 3.2556E-003 x **Ton**

Graphite

SR = -0.63818 + 0.65037 x **Ip** +3.25562E-003x **Ton**

Brass

SR = -1.17997 + 0.65037x **Ip** +E+13.25562E-003x **Ton**

7.1.3.3 Effect of current:

It is evident from perturbation plot that SR is highly sensitive to peak current. SR tends to increase considerably with increase in peak current for any value of pulse on time for all the three tools as shown in Figure 46, 47 and 48.

7.1.3.4 Effect of T_{on} and Discharge current on SR for different tools

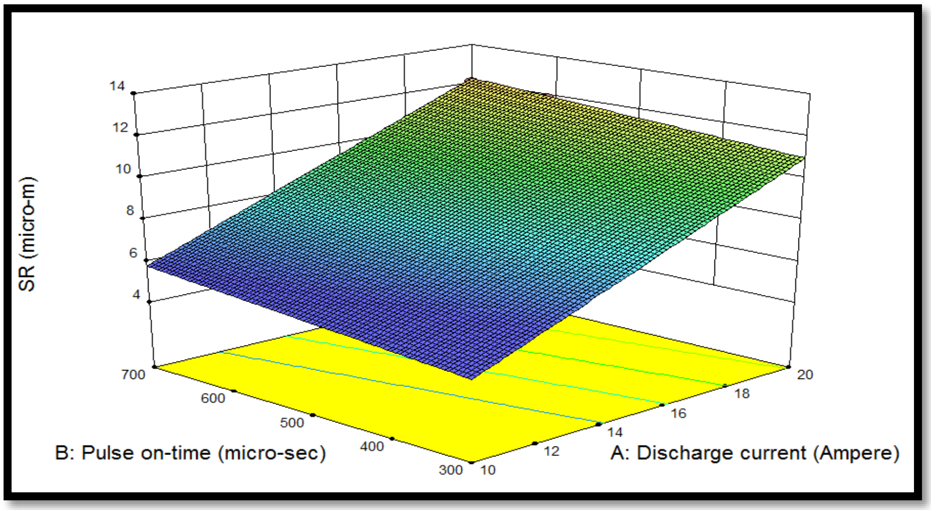

Figure 46 Effect on SR by Copper tool

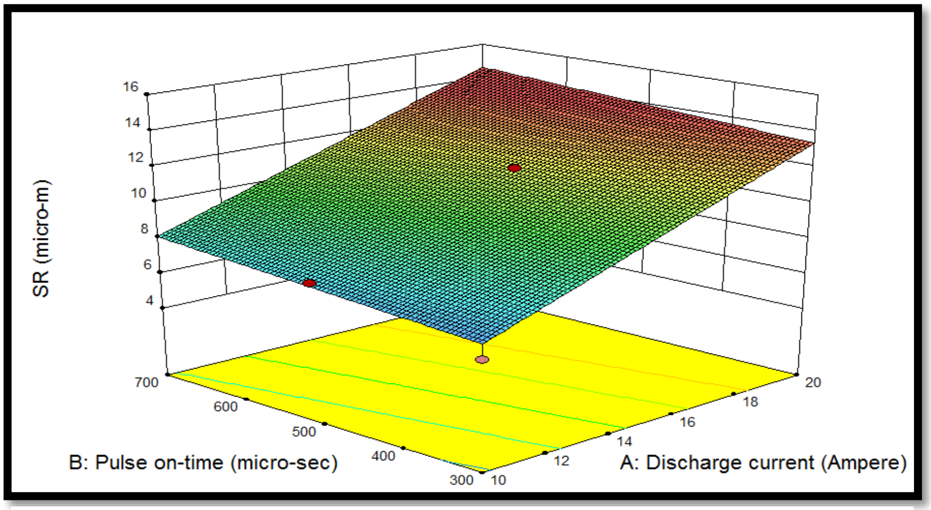

Figure 47 Effect on SR by Graphite tool

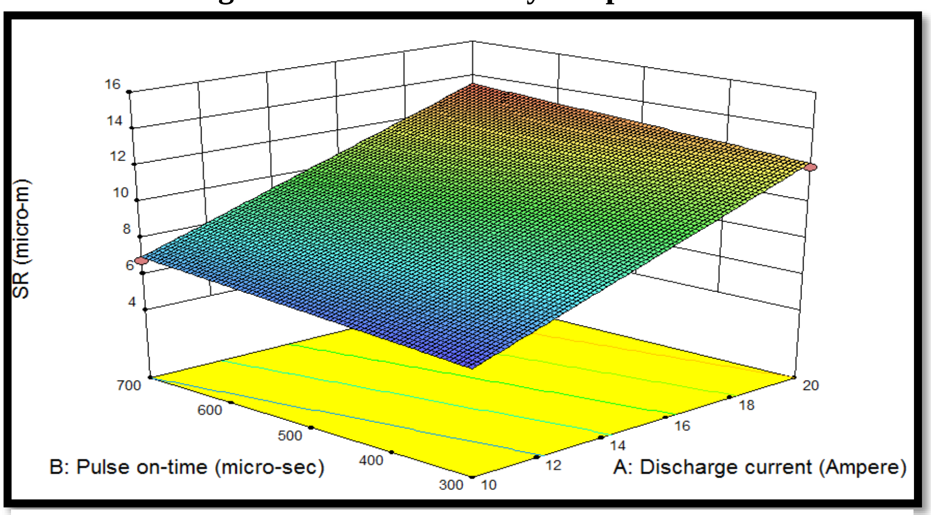

Figure 48 Effect on SR by Brass tool

7.2 Cryogenic Treatment analysis

In cryogenic treatment analysis cryogenic treated tool were used for the machining. The tools were kept in liquid Nitrogen for 24 hrs. The main purpose of using the cryogenic treated tool is to reduce the tool wear. The table for the cryogenic treatment analysis was same as that of non-cryogenic analysis.

7.2.1 For MRR

MRR for the Cryogenic tools has been calculated and tabulated as shown in the table 5. To collect the data regression analysis has been performed. ANOVA has been performed for the data analysis.

The table for experiment is prepared using Design of Expert software version 9. D-optimal design of RSM has been used. A particular range of I/p parameter was feed in the software to prepare the experiment table.

2FI is recommended as statistically significant for analysis by the fit summary table formed by ‘Design Expert’ software. The recommended fit summary is shown in **Table 16.**

The Model F-value of 151.51 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, D, AD, BC, BD are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.

If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.

The "Pred R-Squared" of 0.9561 is in reasonable agreement with the "Adj R-Squared" of 0.9897; i.e. the difference is less than 0.2 was suggested and chosen for regression modelling. The results of the quadratic model in form of ANOVA are given in **Table 15**

Run	I (Amp)	T_{on}(µs)	T_{off}(µs)	Tool	MRR(mm^3/sec)	TWR(mm^3/sec)	SR(µm)
1	16	300	200	Gr	18.3046	2.2156	13.62
2	16	500	600	Cu	24.0484	1.0153	10.58
3	10	500	200	Gr	10.3203	1.3251	7.68
4	10	300	200	Br	1.3214	0.9193	6.87
5	20	500	600	Cu	32.9291	1.6692	12.67
6	10	700	400	Br	1.8912	1.2143	7.18
7	17	600	200	Br	3.8814	2.1184	12.07
8	16	500	400	Gr	19.5234	2.5431	12.31
9	20	700	600	Br	7.7109	4.5134	16.09
10	20	500	600	Gr	20.62511	3.7421	14.97
11	20	600	400	Cu	35.8281	1.9142	13.76
12	10	300	400	Gr	6.9121	1.0135	6.87
13	20	300	600	Cu	29.0156	1.3518	11.34
14	20	700	400	Cu	38.5547	2.3849	13.43
15	10	700	600	Cu	18.1343	0.4765	6.5
16	14	700	600	Gr	16.1532	1.9136	12.06
17	12	400	600	Br	2.5015	1.8145	8.87
18	20	300	400	Br	5.5078	3.9124	13.45
19	14	700	300	Gr	15.9143	1.8341	10.98
20	10	700	200	Cu	16.1411	0.2384	7.93
21	14	400	200	Cu	20.567	0.8532	8.98
22	10	500	400	Gr	11.0158	1.4167	8.67
23	10	300	600	Gr	7.0091	1.021	9.98

Table 15 Experiment table used for cryogenic treated tools

Source	Sequential p-value	Adjusted R-squared	Predicted R-squared	
Linear	< 0.0001	0.9113	0.8654	
2FI	0.0004	0.9897	0.9561	Suggested
Quadratic	0.9637	0.9843	0.8381	
Cubic				Aliased

Table 15 Summary of model test fitting

Source	Sum of Squares	Df	Mean Square	F-Value	Prob > F	
Model	2619	14	187.11	151.51	< 0.0001	Significant
A-Ip	503.83	1	503.83	407.97	< 0.0001	
B-Ton	41.33	1	41.33	33.47	0.0004	
C-Toff	2.30	1	2.30	1.87	0.2091	
D-Electrode	1470.95	2	735.48	595.54	<0.0001	
AB	0.20	1	0.20	0.17	0.6944	
AC	2.05	1	2.05	1.66	0.2334	
AD	125.66	2	62.83	50.88	< 0.0001	
BC	6.68	1	6.68	5.41	0.0485	
BD	20.42	2	10.21	8.27	0.0113	
CD	6.15	2	3.07	2.49	0.1444	
Residual	9.88	8	1.23			
Cor Total	2629.37	22				
Std. Dev.	1.11		R-Squared		0.9962	
Mean	15.82		Adj R-Squared		0.9897	
C.V.%	7.03		Pred R-Squared		0.9561	
PRESS	115.41		Adeq Precision		41.475	

Table 16 ANOVA table for MRR before backward elimination

7.2.1.1 Modeling

After eliminating the non-significant terms, the final response equation for MRR has been obtained by ‘Design Expert’ software and is given as follows:

Final equation in terms of actual factors:

Copper

MRR = -12.27681+ 2.09378 x **Ip** + 0.0102046x **Ton -** 0.0146160x **Toff** +2.51432E-005 x **Ip** x **Ton**

Graphite

MRR = -0.23103-+ 1.25197 x **Ip** -3.0942EE-003 x **Ton** -0.014616 x **Toff** + 2.51432E-005 x **Ip** x **Ton**

Brass

MRR = +0.89850 + 0.47839 x **Ip** -7.08420E-003 x **Ton** -0.014616 x **Toff** + 2.51432E-005 x **Ip** x **Ton**

Source	**Sum of Squares**	**Df**	**Mean Square**	**F-Value**	**Prob > F**	
Model	23.94	8	2.99	30.49	< 0.0001	significant
A-Ip	15.08	1	15.08	153.68	< 0.0001	
B-Ton	0.22	1	0.22	2.21	0.1591	
D-Electrode	9.45	2	4.73	48.17	< 0.0001	
AD	0.74	2	0.37	3.80	0.0482	
CD	0.75	2	0.38	3.83	0.0471	
Residual	1.37	14	0.098			
Cor Total	25.31	22				
Std. Dev.	0.31		R-Squared		0.9457	
Mean	1.80		Adj R-Squared		0.9147	
C.V.%	17.36		Pred R-Squared		0.8010	
PRESS	5.04		Adeq Precision		20.902	

Table 17 ANOVA table for MRR after backward elimination

The Model F-value of 174.03 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, B, D, AD, BC, BD are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Pred R-Squared" of 0.9769 is in reasonable agreement with the "Adj R-Squared" of 0.9874;i.e. the difference is less than 0.2. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 43.552 indicates an adequate signal. This model can be used to navigate the design space.

7.2.1.2 Results and discussion

The perturbation plot shown in **Figure 49,50 and 51** helps to compare the effect of all the factors at a particular point in the design space. One factor was changed while holding all the other factors constant to plot the response over its range. The midpoint of all the factors sets as the reference point by default in “Design-Expert” software. A steep slope for current (A) and pulse on time (B) for the material shows that the response is highly sensitive to that factor however relatively flat lines for pulse off time (C) is less sensitivity to these factors. The factors affecting the response most significantly if more than two factors are present can be easily analysed by the perturbation plot

7.2.1.3 Effect of current:

It is evident from perturbation plot that MRR is highly sensitive to peak current. MRR tends to increase considerably with increase in peak current for any value of pulse on time as shown in **Figure 52,53 and 54**. Hence, maximum MRR is obtained at high peak current and high pulse on time. It is because as the pulse current increases it creates strong spark that generate very high temperature and more material is removed from the surface (Pradhan and Biswas, 2008). The trend for variation of MRR along with current is well confirmed with published literature (Pandey and Shan, 2008; Garg *et* al., 2010). For all the three tools, discharge current plays a very important role.

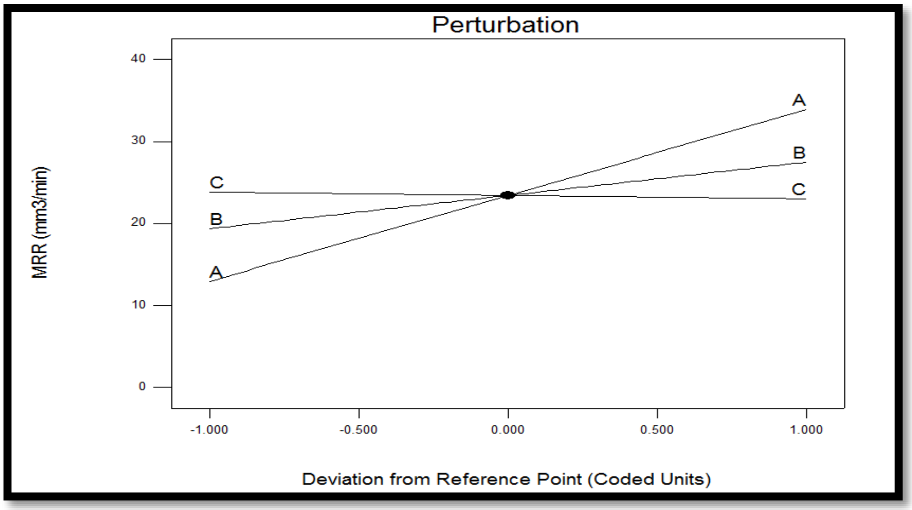

Figure 49 Perturbation plot of MRR with discharge current for Copper tool

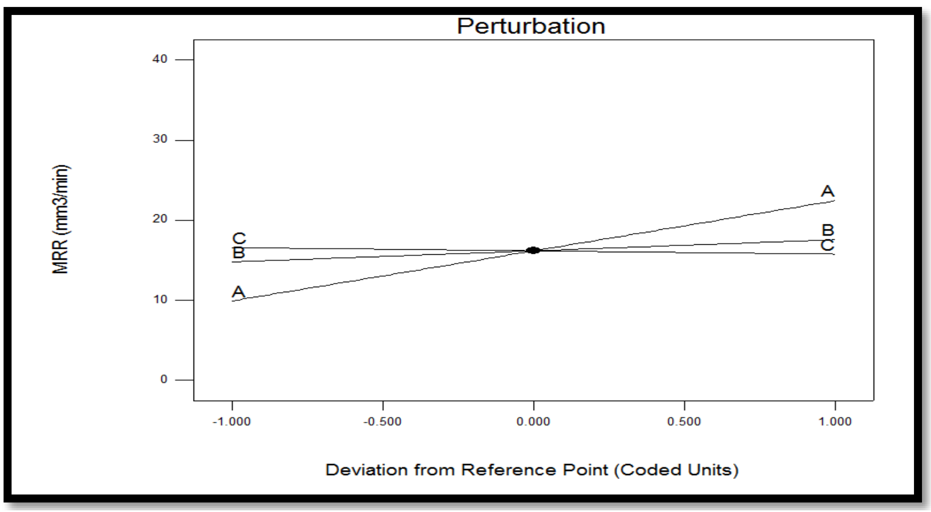

Figure 50 Perturbation plot of MRR with discharge current for Graphite tool

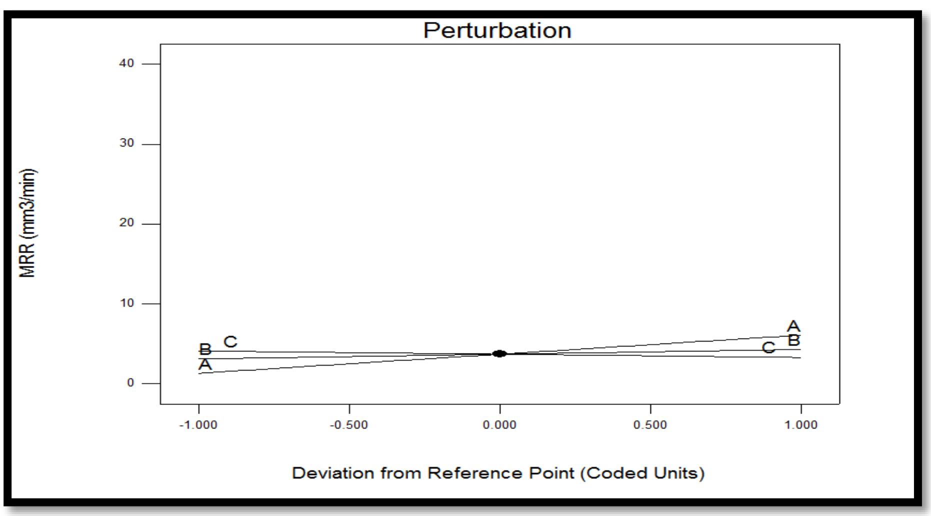

Figure 51 Perturbation plot of MRR with discharge current for Brass tool

7.2.1.4 Effect of T_{on} and Discharge current on MRR for different tools

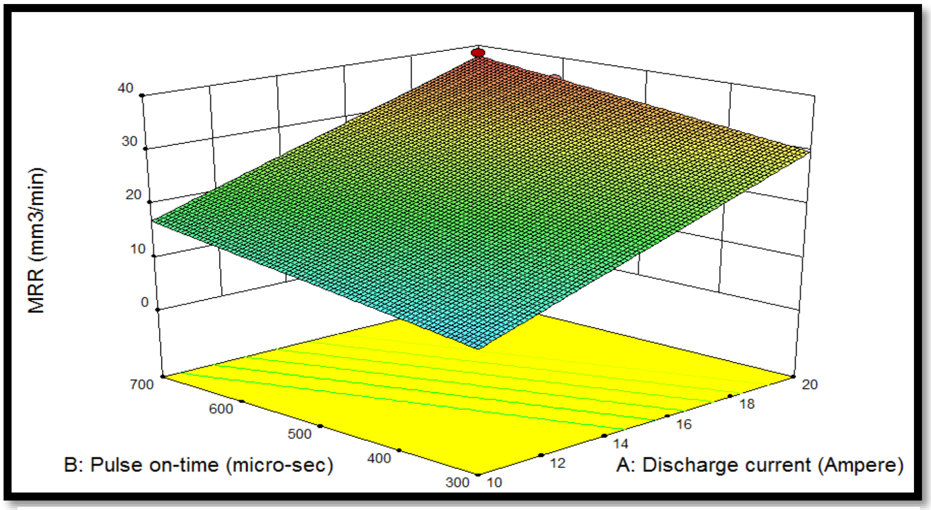

Figure 54 Effect on MRR by Copper tool

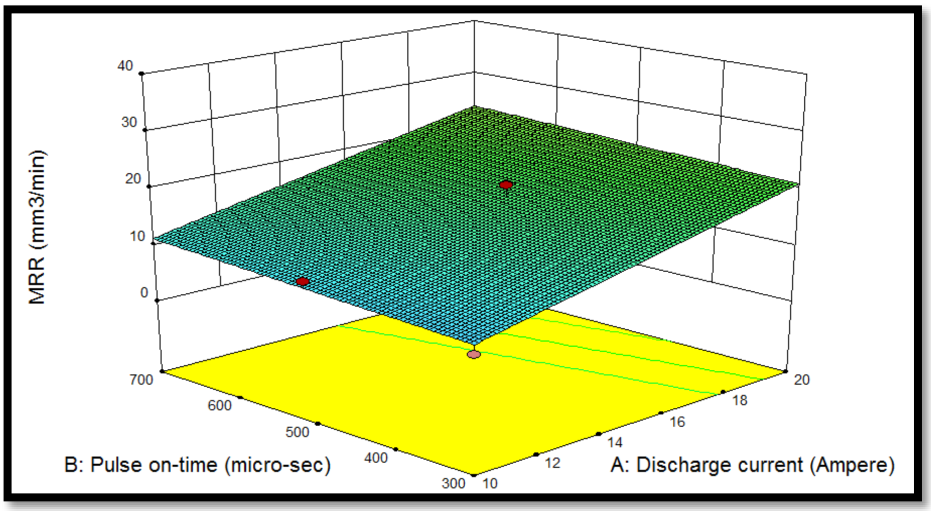

Figure 53 Effect on MRR by Graphite tool

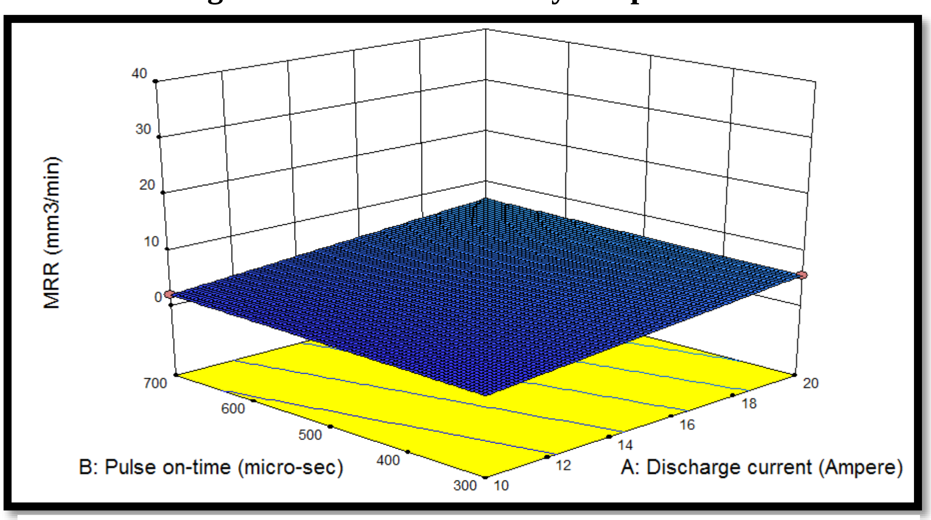

Figure 52 Effect on MRR by Brass tool

7.2.2 Analysis of TWR

Source	Sequential p-value	Adjusted R-squared	Predicted R-squared	
Linear	< 0.0001	0.8476	0.7606	Suggested
2FI	0.0459	0.9344	0.9927	Suggested
Quadratic	0.2410	0.9515	0.5674	
Cubic				Aliased

Table 18 Summary of model test fitting for TWR

Source	Sum of Squares	Df	Mean Square	F-Value	Prob > F	
Model	24.71	14	1.76	23.38	< 0.0001	significant
A-Ip	15.23	1	15.23	201.84	< 0.0001	
B-Ton	0.11	1	0.11	1.46	0.2608	
C-Toff	0.24	1	0.24	3.12	0.1155	
D-Electrode	8.87	2	4.44	58.78	<0.0001	
AB	*4.469E-003*	1	*4.469E-003*	0.059	0.8139	
AC	0.16	1	0.16	2.17	0.1793	
AD	0.35	2	0.17	2.31	0.1614	
BC	0.17	1	0.17	2.25	0.1723	
BD	0.36	2	0.18	2.38	0.1546	
CD	0.66	2	0.33	4.35	0.0528	
Residual	0.60	8	0.075			
Cor Total	25.31	22				
Std. Dev.	0.27		R-Squared		0.9761	
Mean	1.80		Adj R-Squared		0.9244	
C.V.%	15.23		Pred R-Squared		0.4927	
PRESS	12.84		Adeq Precision		18.776	

Table 19 ANOVA table for TWR before backward elimination

The Model F-value of 23.38 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, Dare significant model terms. Values greater than

0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Pred R-Squared" of 0.4927 is in reasonable agreement with the "Adj R-Squared" of 0.9344; i.e. the difference is less than 0.2.

Source	**Sum of Squares**	**Df**	**Mean Square**		**F-Value**	**Prob > F**	
Model	23.94	8	2.99		30.49	< 0.0001	significant
A-Ip	15.08	1	15.08		153.68	< 0.0001	
B-Ton	0.22	1	0.22		2.21	0.1591	
D-Electrode	9.45	2	4.73		48.17	< 0.0001	
AD	0.74	2	0.37		3.80	0.0482	
CD	0.75	2	0.38		3.83	0.0471	
Residual	1.37	14	0.098				
Cor Total	25.31	22					
Std. Dev.	0.31			R-Squared		0.9457	
Mean	1.80			Adj R-Squared		0.9147	
C.V.%	17.36			Pred R-Squared		0.8010	
PRESS	5.04			Adeq Precision		20.902	

Table 20 ANOVA table for TWR after backward elimination

The Model F-value of 30.49 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, D, AD, CD are significant model terms. Values greater than 0.1000 indicate the model terms are not significant.If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Pred R-Squared" of 0.8010 is in reasonable agreement with the "Adj R-Squared" of 0.9147; i.e. the difference is less than 0.2. "Adeq Precision" measures the signal to noise ratio

7.2.2.1 Results and discussion

The perturbation plot shown in Figure helps to compare the effect of all the factors at a particular point in the design space. One factor was changed while holding all the other factors constant to plot the response over its range

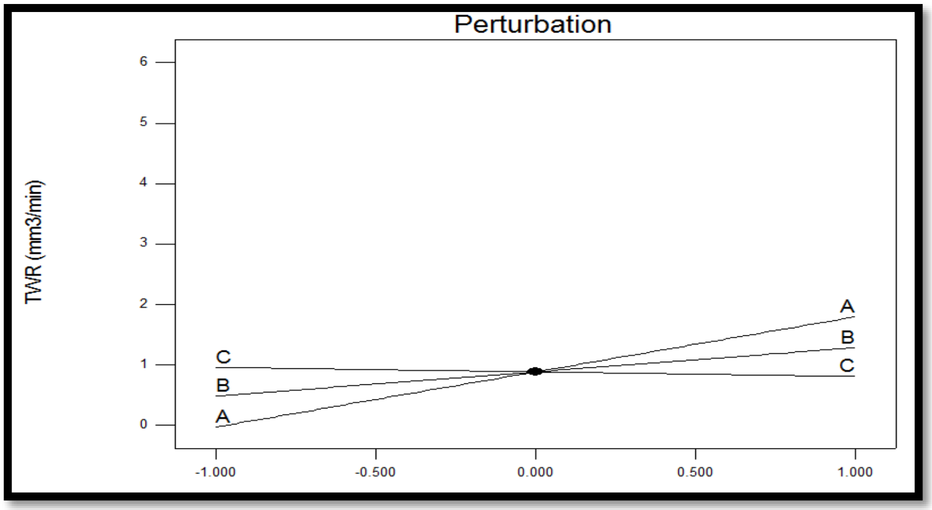

Figure 55 Perturbation plot of TWR with discharge current for Copper tool

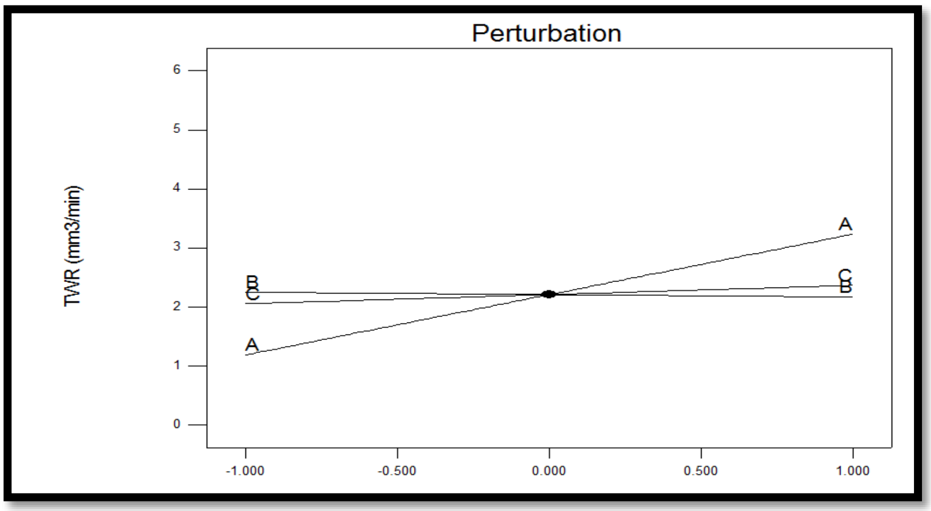

Figure 56 Perturbation plot of TWR with discharge current for Graphite tool

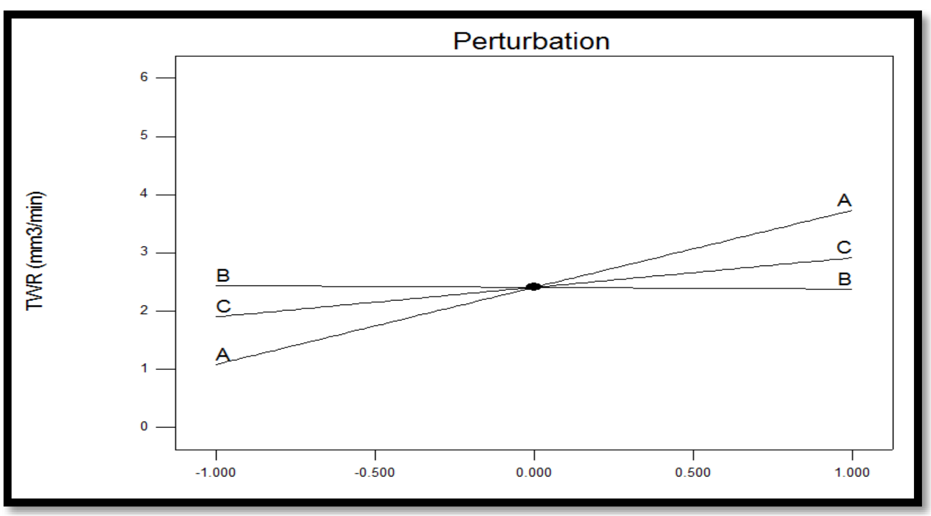

Figure 57 Perturbation plot of TWR with discharge current for Brass tool

7.2.2.2 Effect of current:

It is evident from perturbation plot that TWR is highly sensitive to peak current. TWR tends to increase considerably with increase in peak current for any value of pulse on time as shown in **Figure**

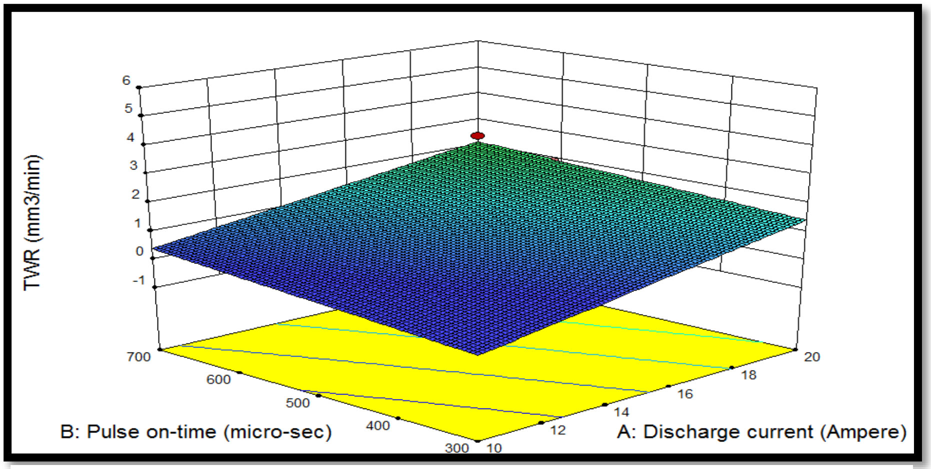

Figure 58 Effect on TWR by Copper tool

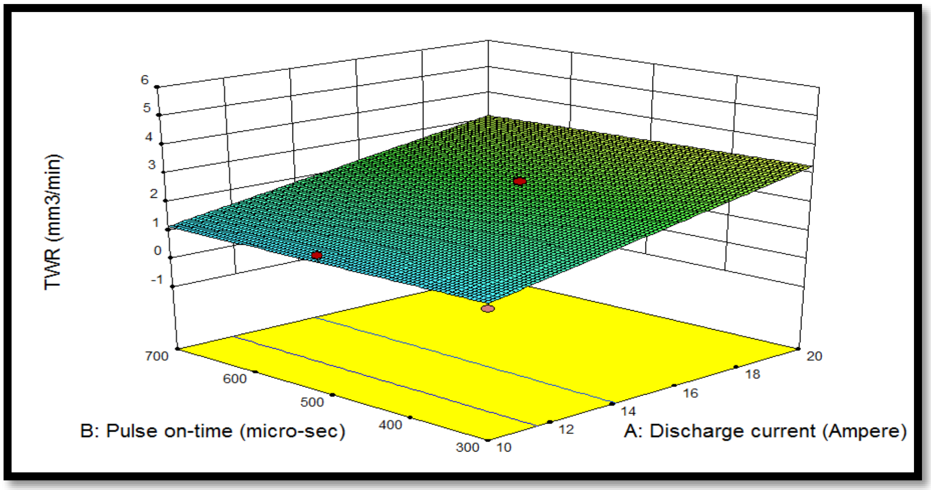

Figure 59 Effect on TWR by Graphite tool

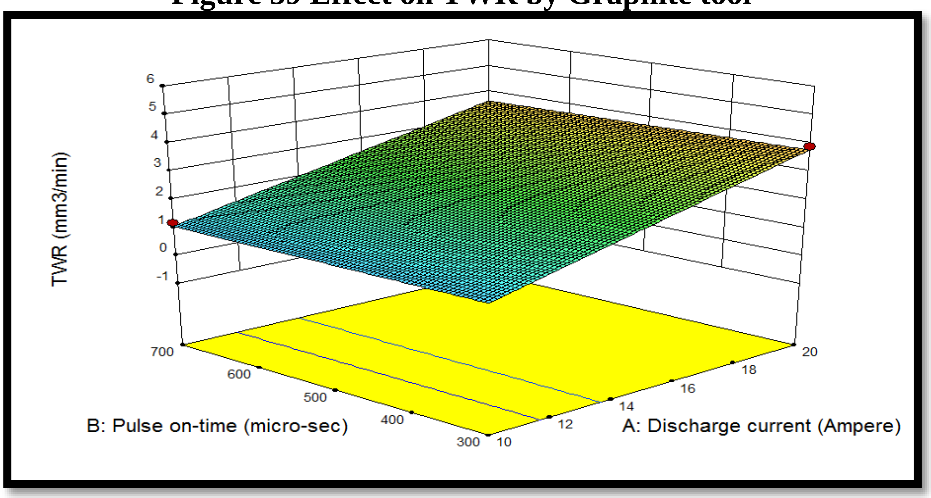

Figure 60 Effect on TWR by Brass tool

7.2.2.3 Modeling

After eliminating the non-significant terms, the final response equation for MRR has been obtained by ‘Design Expert’ software and is given as follows:

Final equation in terms of actual factors:

Copper

TWR = -1.07487+ 0.15579 x **Ip** - 4.86042E-004 x **Toff**

Graphite

MRR = -1.27387 + 0.22732 x **Ip** + 3.491323E-004 x **Toff**

Brass

MRR = -2.53419 + 0.26793 x **Ip** +2.43818E-003 x **Toff**

7.2.3 Analysis of SR

Source	Sequential p-value	Adjusted R-squared	Predicted R-squared	
Linear	< 0.0001	0.8900	0.8305	Suggested
2FI	0.6878	0.8704	0.0533	
Quadratic	0.4634	0.8706	-1.3293	
Cubic				Aliased

Table 21 Summary of model test fitting for SR

The Model F-value of 36.61 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, Dare significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Pred R-Squared" of 0.8305 is in reasonable agreement with the "Adj R-Squared" of 0.8900; i.e. the difference is less than 0.2.

Source	Sum of Squares	Df	Mean Square	F-Value	Prob > F	
Model	162.85	5	32.57	36.61	< 0.0001	significant
A-Ip	148.09	1	148.09	166.45	< 0.0001	
B-Ton	3.25	1	3.25	3.65	0.0730	
C-Toff	0.048	1	0.048	0.054	0.8194	
D-Electrode	19.27	2	9.63	10.83	0.0009	
Residual	15.12	17	0.89			
Cor Total	177.98	22				
Std. Dev.	0.94		R-Squared		0.9150	
Mean	10.73		Adj R-Squared		0.8900	
C.V.%	8.79		Pred R-Squared		0.8305	
PRESS	30.17		Adeq Precision		17.826	

Table 22 ANOVA table for SR

7.2.3.1 Modeling

After eliminating the non-significant terms, the final response equation for MRR has been obtained by 'Design Expert' software and is given as follows:

Final equation in terms of actual factors:

Copper

SR = -1.62270+ 0.67118 x **Ip** +2.48134E-003 x **Ton**

Graphite

SR = +0.65871 + 0.67118 x **Ip** + 2.48134E-003 x **Ton**

Brass

SR = -0.44154 + 0.67118 x **Ip** +2.43818E-003 x **Ton**

7.2.3.2 Results and discussion

The perturbation plot shown in Figure helps to compare the effect of all the factors at a particular point in the design space. One factor was changed while holding all the other factors constant to plot the response over its range

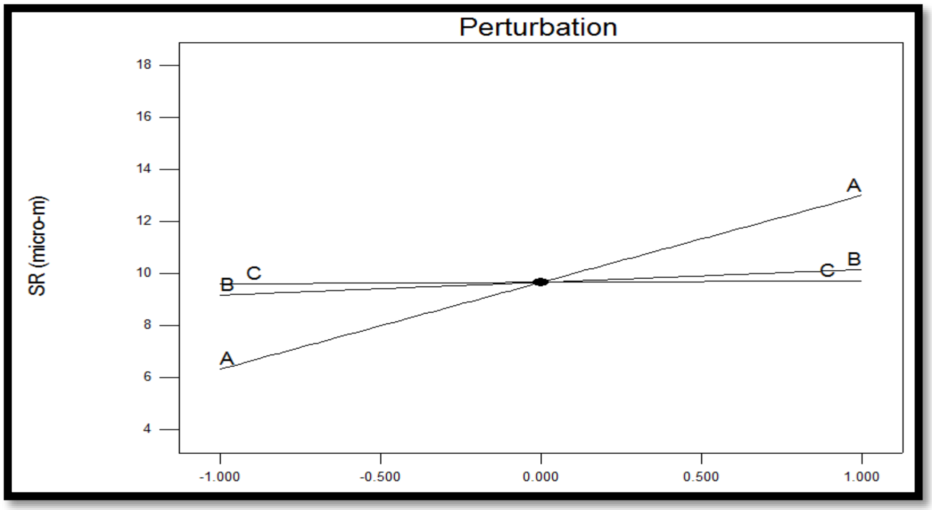

Figure 61 Perturbation plot of SR with discharge current for Copper tool

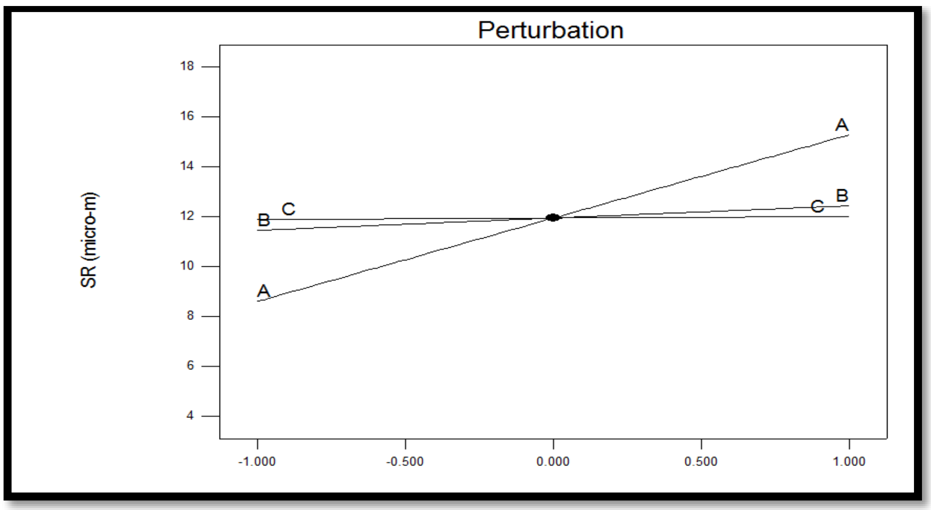

Figure 62 Perturbation plot of SR with discharge current for Graphite tool

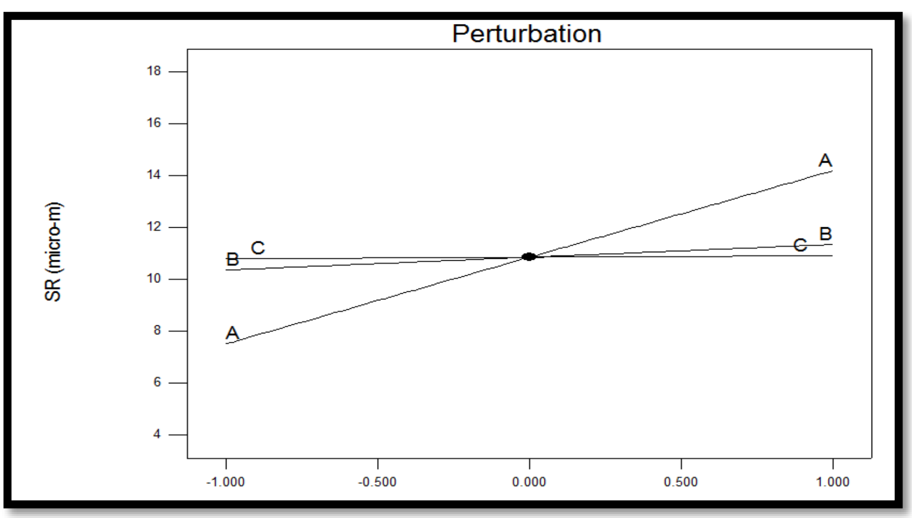

Figure 63 Perturbation plot of SR with discharge current for Brass tool

7.2.3.2 Effect of T_{on} and Discharge current on SR for different tools

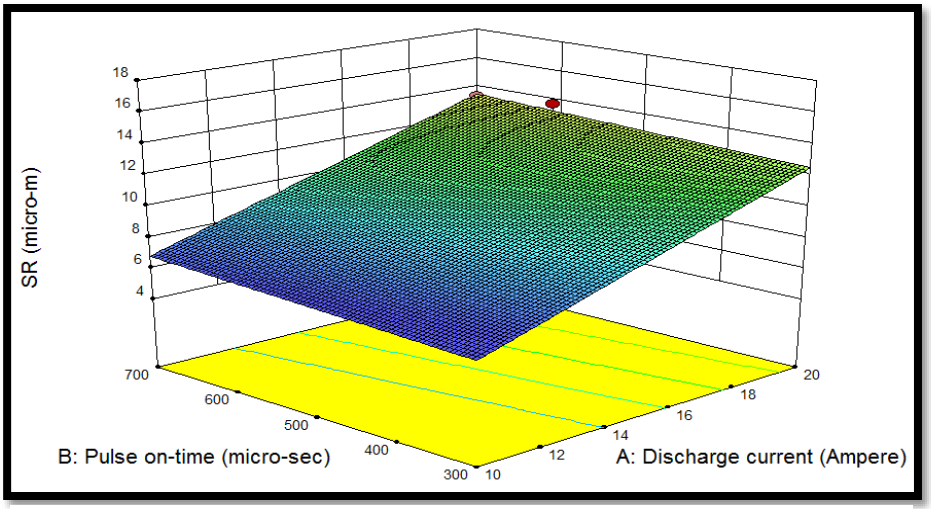

Figure 64 Effect on SR by Copper tool

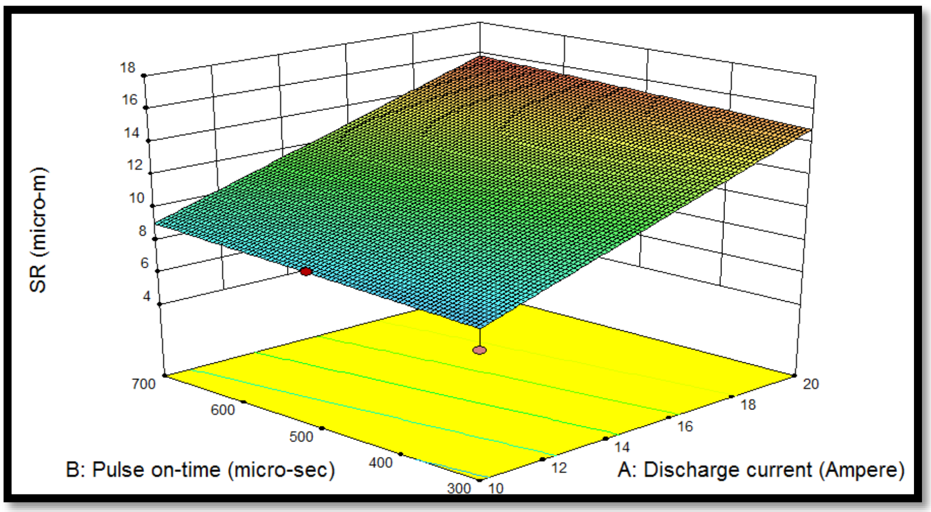

Figure 65 Effect on SR by Graphite tool

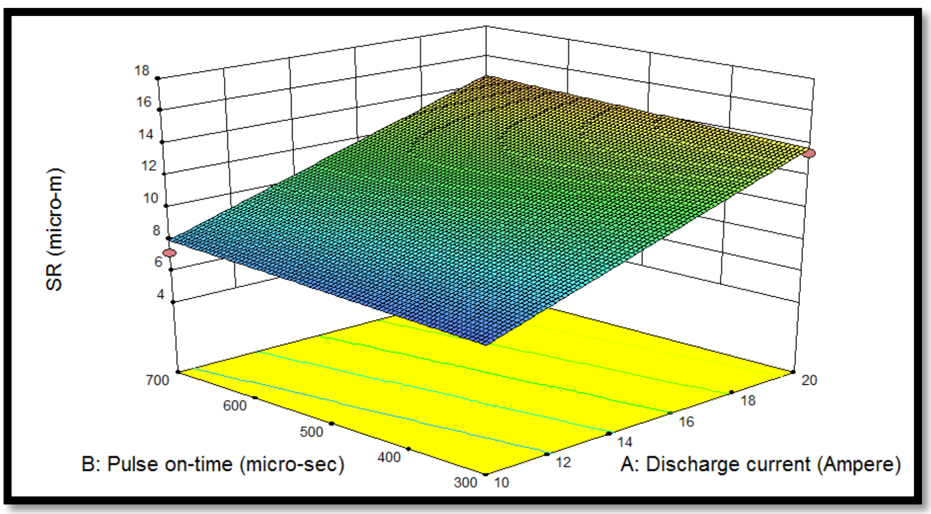

Figure 66 Effect on SR by Brass tool

7.3 Optimization of Parameter

7.3.1 For Non-Cryogenic treatment

The optimization module in "Design-Expert" software was applied to search for a combination of factor levels that simultaneously satisfy the requirements placed on each of the responses and factors. Simultaneous optimization of multiple responses was performed numerically. Numerical optimization optimizes any combination of one or more goals. The goals may apply to either factors or responses. The possible goals are: maximize, minimize, target, within range, none (for responses only) and set to an exact value (factors only). A minimum and maximum level must be provided for each parameter included in the optimization. A weight can be assigned to a goal to adjust the shape of its particular desirability function. The default value of one creates a linear ramp function between the low value and the goal or the high value and the goal. The "importance" of a goal can be changed in relation to the other goals. The default is for all goals to be equally important at a setting of 3. Desirability is an objective function that ranges from zero outside of the limits to one at the goal. The numerical optimization finds a point that maximizes the desirability function.

Name	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Importance
A: Current	Is in range	10	20	1	1	3
B: Pulse on time	Is in range	300	700	1	1	3
C: Pulse off time	Is in range	200	600	1	1	3
MRR	Maximize	3.1615	27.5391	1	1	3
TWR	Minimize	0.8951	7.0707	1	1	3
SR	Minimize	5.8	13.78	1	1	3

Table 23 Limiting Range of I/p and O/p Parameter

S no.	Ip	Ton	Toff	Tool	MRR	TWR	SR	Desirability	
1	11.406	700	494.138	Cu	12.150	2.404	6.706	0.674	Selected
2	12.468	536.483	200.005	Cu	11.585	2.290	6.864	0.614	
3	13.967	387.717	599.979	Cu	12.024	2.452	7.355	0.603	
4	13.337	300	212.677	Gr	13.415	1.605	9.012	0.606	selected
5	13.707	406.716	600	Gr	13.981	1.723	9.601	0.586	
6	15.382	300	599.964	Br	5.996	2.262	9.133	0.375	Selected
7	14.259	629.023	599.9733	Br	5.811	2.330	9.542	0.354	

Table 24 Optimization table for I/p Parameter used in non-cryogenic analysis

7.3.2 For Cryogenic treatment

Name	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Importance
A: Current	Is in range	10	20	1	1	3
B: Pulse on time	Is in range	300	700	1	1	3
C: Pulse off time	Is in range	200	600	1	1	3
MRR	Maximize	1.3214	38.5547	1	1	3
TWR	Minimize	0.2384	4.5134	1	1	3
SR	Minimize	6.5	16.09	1	1	3

Table 25 Limiting range of I/p and O/p parameter

S no.	Ip	Ton	Toff	Tool	MRR	TWR	SR	Desirability	
1	10	699.997	599.991	Gr	11.913	1.209	9.109	0.543	Selected
2	10	699.995	520.455	Gr	11.676	1.181	9.107	0.540	
3	10	608.183	599.998	Gr	10.812	1.209	8.880	0.529	
4	10.923	699.999	599.99	Cu	19.555	0.335	7.445	0.756	selected
5	11.402	700	589.207	Cu	20.526	0.415	7.767	0.754	
6	11.342	699.997	228.394	Cu	19.324	0.581	7.727	0.729	
7	13.513	300.001	200	Br	3.823	1.574	9.372	0.319	Selected
8	14.259	300	200.002	Br	4.266	1.882	9.993	0.316	
9	14.913	382.065	200	Br	4.324	1.949	10.516	0.304	

Table 26 Optimization table for I/p Parameter used in Cryogenic analysis

1. In non-cryogenic treated electrode highest MRR has been observed by Copper followed by Graphite and then Brass.
2. Minimum tool wear has been observed by Graphite tool followed by Brass and Copper in case of non-cryogenic treated electrode.
3. The value of surface roughness was observed best by Graphite tool followed by Copper and Brass in Non-cryogenic electrodes.
4. In case of cryogenic treated electrode higher MRR has been observed by Copper followed by Graphite and Brass.
5. Minimum TWR has been observed by Copper electrode followed by Brass and Graphite in case of cryogenic treated electrode.
6. Cryogenic treatment produces poor surface finish as compared to non-cryogenic tools.
7. Cryogenic treatment increases MRR and reduces TWR gradually in case of copper electrode.
8. For graphite tool cryogenic treatment increases MRR gradually however tool wear increases in initial state but after a certain point it value decrease gradually
9. In case of Brass tool, cryogenic treatment reduces both MRR and TWR gradually.
10. The optimization parameter for non-cryogenic treated electrode were as follows:

    Graphite tool = A- 11, Ton- 300, Toff- 500

    Brass tool = A- 13, Ton- 300, Toff- 200

    Copper tool = A- 11, Ton- 700, Toff- 500
11. The optimization parameter for Cryogenic treated electrode were as follows:

    Graphite tool = A- 10, Ton- 700, Toff- 600

    Brass tool = A- 14, Ton- 300, Toff- 200

    Copper tool = A- 11, Ton- 700, Toff- 600

In the present study a comparison is made between cryogenic and non-cryogenic treated tools used during Electrical discharge machining of superalloy. There is wide future scope in the field of superalloy because of their wide use in high temperature and corrosion resistance environment.

- In this study Ni-Cr based superalloy has been used but there are many other superalloy such as Nickel-Molybdenum, Nickel-Copper alloy which can be used for further study.
- Response surface methodology (RSM) was applied for analysis and modelling of observations. It is suggested that other approaches like Taguchi, ANN may be applied for similar problem and results should be compared to establish a correlation between them.
- There are many other performance measures affecting machining accuracy like Taper cut, over cut and micro hardness etc. These parameters were not included in this study. These may be considered for future research work.
- The selected design parameters were varied in limited ranges and levels in this research work. These parameters may be investigated in extended range with more levels. Also, there are several other important electrical and non-electrical parameters like flushing pressure, polarity, tool holding time etc which were not considered in this study. Impact of these parameters may also be investigated further.

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