A STUDY OF PROCESS PARAMETERS DURING ELECTRIC DISCHARGE MACHINING ON INCONEL

A Thesis submitted in partial fulfilment of the requirement for the award of the degree of **MASTER OF MECHANICAL ENGINEERING**
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CERTIFICATE OF RECOMMENDATION

We hereby recommend that the thesis prepared under our supervision by **Mr. Somnath Mondal**, entitled "**A Study of Process Parameters during Electrode Discharge Machining on Inconel**" be accepted in partial fulfilment of the requirements for awarding the degree of Master of Mechanical Engineering under Department of Mechanical Engineering of Jadavpur University, Kolkata-700032.

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CERTIFICATE OF APPROVAL*

The foregoingthesis is hereby approved as a creditable study of an engineering subject carried out and presented in a manner of satisfactory to warrant its acceptance as a pre-requisite to the degree for which it has been submitted.It is understood that by this approval,the undersigned does not necessarily endorse or approve any statement made, opinion expressed and conclusion drawn therein but the thesis only for the purpose for which it has been submitted.

Final Examination for

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CHAPTER 1
INTRODUCTION

1.1 OVERVIEW

Material removal processes can be further divided intoEDM (electric discharge machining) is widely used and has become a significant process in modern manufacturing. In EDM material is removed using a spark between two electrically conductive materials. Basic facts of spark erosion were known since last 200 years.Erosion of material was first reported by Joseph Priestily in 1878.The beginning of EDM came during the second world war,when two Russian Physicists B.R Lazarenko and N.I.Lazarenko published their study on the "Inversion of the Electric Discharge Wear Effect",which related to the application to manufacturing technology of the capacity of electrical discharges,under controlled distribution to remove metal.EDM was being used at that time to remove broken taps and drills.

The EDM process is similar to conventional cutting process. In EDM the tool is an electrode and its movement is controlled precisely using servo drives. Cutting energy is provided by means of short duration electric pulses. Discharge is submerged in the dielectric medium so as to concentrate the spark energy into a smaller area.EDM has paved a way to machine high strength temperature resistance alloys and other hard to machine conducting materials.

1.2 MANUFACTURING PROCESSES AND ITS CLASSIFICATION

Manufacturing process can be broadly divided into two groups:

1.Primary manufacturing processes

2.Secondary manufacturing processes

The primary manufacturing processes provide basic shape and size to the material as per requirement.

The secondary manufacturing processes provide the final shape and size with tighter control on the dimensions, surface characteristics, etc. of the workpiece. Material removal process that comes under Secondary manufacturing processes can be further divided into two groups. They are

1. Conventional machining process

2.Non-traditional machining process

Example of conventional machining processes are turning, boring, milling, shaping, broaching, slotting, grinding etc.

Examples of non-conventional machining processes are abrasive jet machining, ultrasonic machining, water jet and abrasive water jet machining, electro discharge machining, electrochemical machining.

1.2.1 Need for Non-conventional/Non-traditional/Advanced Machining Processes

1. Extremely hard and brittle materials are difficult to machine by conventional machining processes can be easily machined with the help of Non-traditional machining.
2. Complex shape object can be easily machined with the help of Non-traditional machining
3. To get higher accuracies and better surface finish Non-traditional machining is preferred over traditional machining.
4. Non-traditional processes are preferred in industries where high and continuous production is required, as they can work continuously with very little downtime.
5. Tool wear is less in case of Non-traditional machining over traditional machining
6. when the workpiece is too flexible or slender to support the cutting forces, it is preferable to use non-conventional machining process to avoid any accident.

1.2.2 Types of Non-Conventional /Non-Traditional/Advanced Machining Processes

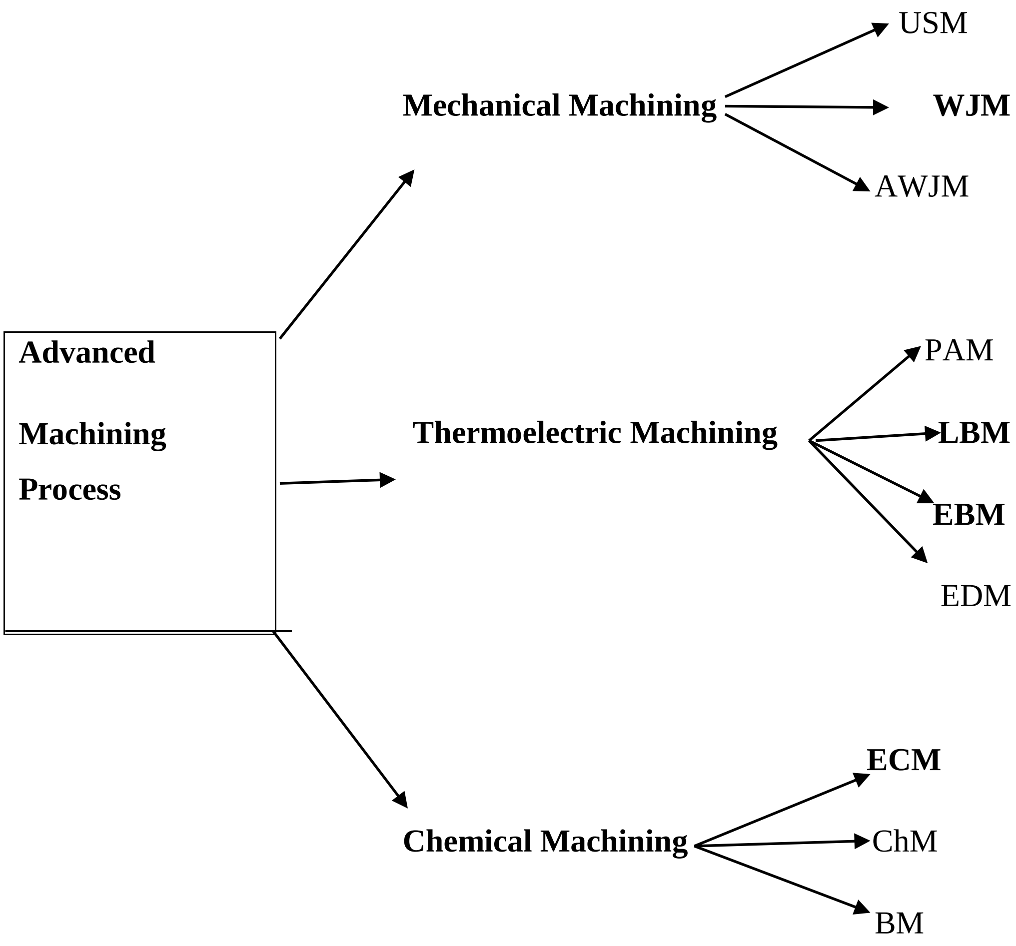
Different Non-Traditional processes that use the different types of energy for the material removal are classified as shown below.

1.Mechanical Machining: Here Kinetic energy of either abrasive or water jet is utilised to remove excess material from the workpiece and the removal of material occurs mainly by abrasion is called as Mechanical Machining. Some of the examples of Mechanical Machiningare Abrasive jet machining, Abrasive water jet machining, Ultrasonic machining, water jet machining etc.

2.Electrochemical Machining: The process in which anodic dissolution occurs is known as Electrochemical machining. Examples of electrochemical machining are Electrochemical Machining, Electrochemical Grinding, Electrojet drilling etc.

3.Thermoelectric Machining: Thermoelectric machining is the process in which the energy supplied to the workpiece is in the form of heat, light, or electron bombardment and the input energy is concentrated over a small area of the workpiece. Examples of thermoelectric machining are Electro-discharge machining, Electron beam machining, Laser beam machining, Plasma arc machining etc.

4.Chemical machining: Chemical machining is the material removal process for the production of desired shapes through selective or overall of material by controlled chemical attack with acids and alkalis. Examples of chemical machining are Chemical milling, Chemical Blanking, Electropolishing, Photochemical machining etc.



1.3 Electric Discharge Machining (EDM)

1.3.1 Introduction

The Electric Discharge machining(EDM) process involves a controlled erosion of electrically conductive material by the initiation of rapid and repetitive spark discharge between the electrode tool (cathode) and workpiece (Anode) separated by a small gap (0.01 to 0.50 mm) known as spark gap.

EDM is a process of cratering out of metals using a spark. Each spark of thermal power concentration of ten to the power eight W/square mm capable of melting or vaporizing small amount of work material and tool is used. The machining process involves controlled erosion of electrically conductive materials by initiation of rapid and repetitive electrical spark discharge between the tool and workpiece separated by a dielectric fluid medium. A suitable gap known as spark gap is maintained between the tool and the workpiece to cause the spark discharge.

1.3.2 Basic Principle of EDM

When a suitable voltage is applied across the two electrodes which are separated by a dielectric, the dielectric breaks down, a conducting electrical path is developed for spark discharge owing to ionization of the fluid medium and thereby causes a current to flow. Billions of electrons are generated in each spark and thousands of arcs initiated in each second to produce a true replica of the tool surface on to the workpiece. The amount of energy contained in each spark is discrete in nature and can be controlled to control the process parameters and machine removal rate. The temperature of the spot hot by the spark may rise up to ten thousand degree centigrade causing the work surface to melt and vaporize.

1.3.3 Mechanics of Metal Removal

The sequence of events constituting the process of metal removal from the work surface by a single discharge in EDM process can be explained in the following sequence.

1. When the voltage is applied between the work and tool, separated by the properly chosen spark gap filled with suitable dielectric fluid, the breakdown of the dielectric medium takes place due to strong electrostatic field between the electrodes.
2. The strong electrostatic field produces a cold emission of electrons from cathode (tool) and accelerates it towards anode (work).Thus, a free electron liberated from the cathode

will be accelerated towards the anode by the electric field and electron will acquire high velocity.

3. Free electron will collide with the dielectric fluid while moving through the dielectric medium.
4. If the energy contained by the electron at the instant of collision is not sufficient enough to eject another electron from a dielectric molecule, an electron will rebounce with diminished energy.
5. If the energy contained by the electron at the instant of collision is sufficient enough to eject another electron from a dielectric molecule, then greater number of collisions takes place.
6. Due to this collision, the dielectric fluid molecules will be broken up into electrons and positive ions. Consequentially, a small ionized fluid medium will be formed.
7. Due to this ionization of dielectric fluid column the resistance of fluid layer will decrease and an electrical discharge is initiated with the resulting flow of electrons.
8. Each electrical discharge causes a focused stream of electrons from the cathode towards the anode and ultimately creats compression shock waves on both the electrode surfaces.
9. This phenomenon will take place in microseconds and temperature of the spot will rise up to 10000 degree C.

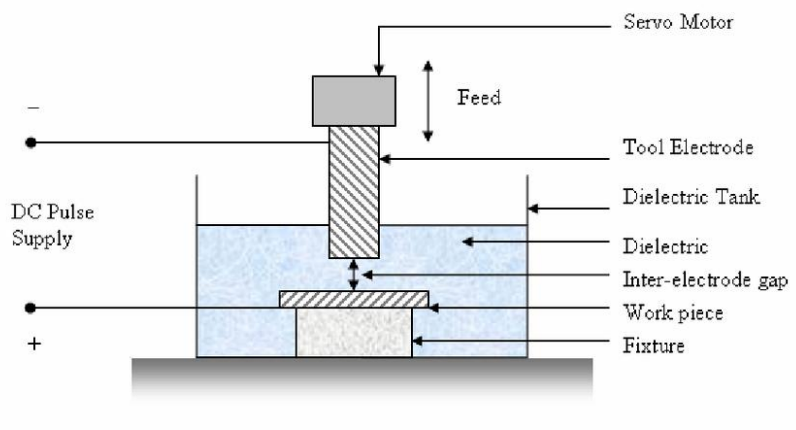


Fig 1.2 Schematic Diagram of EDM

1.3.3 EDM Process Parameters

(a)**Spark On-time:** The duration of time (microsecond) the current is allowed to flow per cycle.Material removal is directly proportional to the amount of energy applied during this on-time.This energy is really controlled by the peak current and the length of the on-time

(b) **Pulse off-time:** The duration of time (microsecond)between the sparks. This time allows the molten material to solidify and to be wash out of the arc gap. This parameter is to affect the speed and the stability of the cut. Thus, if the off-time is too short, it will cause sparks to be unstable.

(c) Discharge current: Current is measured in Amp. Allowed to per cycle. Discharge current is directly proportional to the Material removal rate.

(d) Arc gap: The Arc gap is distance between the electrode and workpiece during the process of EDM. It may be called as spark gap. Spark gap can be maintained by servo system.

(e) Duty cycle: It is a percentage of the on-time relative to the total cycle time. This parameter is calculated by dividing the on-time by the total cycle time.

(g) Diameter of electrode(D): It is the electrode of Cu-tool. The electrode having the diameter of 5mm is used in this experiment. This tool is used not only as a electrode but also for internal flushing.

(h) Over cut: It is a clearance per side between the electrode and the workpiece after the machining operation.

1.3.5 Advantages of EDM

- The process can be applied for all electrically conductive metals and alloys irrespective of their physical, mechanical and metallurgical properties of the work material
- Any complicated shapes can be made on the tool can be reproduced on the workpiece.
- About 80-90% of the EDM work is used in manufacture of tool and die sets for the production of casting, forgings, stampings and extrusions.
- Time of machining is less than conventional machining. This is true especially for hard materials with complex contours.
- EDM can be used to machine extremely hard materials. Hence, distortion of the workpiece due to heat treatment can be eliminated.
- The process is advantageous for tool maintenance and repair work. It is actually suited as a corrective means for completely heat treated finished tooling.
- The error involved in making dies is eliminated to a great extent and is limited to the tool only.
- No mechanical stresses are present in the process except the blasting pressure that occurs during the disappearance of the plasma column.

- EDM gives good surface finish. Surface finish of (0.8-3.0 micrometer) can be achieved.
- The process once setup does not need constant operators monitoring.
- EDM machining produces chip/burr-free work surfaces.
- Soft material electrode can be used to make hard material die. For example, copper tool can be used to make hardened steel dies.
- Considering easier and more economical polishing can be done on the cratering type of the surface developed by EDM.
- Fine holes can be drilled easily in EDM.
- In some materials, longer die life is possible. This is due to hardening of boundary layer by high temperature together with carburizing effect.

1.3.6 Disadvantages of EDM

- Power required for machining in EDM is high compared to conventional machining.
- Reproduction of sharp corners is difficult in EDM. Complex contours are difficult to reproduce.
- Surface cracking may take place in some materials owing to their affinity to become ductile at room temperature especially when higher energy per pulse is used.
- Gap cleaning is very crucial in EDM.
- In most of the jobs, batch sizes of at least 25-30 workpieces are required for economical production.
- EDM produces heat affected zone (HAZ), recast layer and conversion layer. HAZ lead to crack formation.
- In some cases, EDM is confined to small workpieces and produces thermal distortion.
- Electrode wear and over-cut are serious problems of EDM.
- Volumetric metal removal rate in EDM is low.
- Perfect square corners are difficult to make using EDM process.
- Tool wear is high, sometime two or three tools are required to complete the operation. This results in high tool cost.
- The process is not suitable for non-conductive materials. Non-metallic materials such as ceramics, plastics, glass etc. cannot be machined using EDM.
- In some materials, there is decrease in endurance limit up to 15% after EDM.

1.3.7 Applications of EDM

- This is used to machine any hard, tough, brittle, refractory, hard carbides, hardenable steels and exotic material provided it is electrically conductive.
- It is used for manufacture of hardened steel die cavities and miniature holes.
- EDM is useful in economic manufacture of dies for moulding, casting, forging, stamping, coining and forming processes. It is also used for other high precision tool room work.
- EDM is used to make dies/cavities for extrusion and wire drawing processes.
- EDM is used for making tiny holes, orifices and micro-sized slots.
- EDM permits the use of more durable die materials like carbide, hardened steel. Dies are free from burrs and matte finish can be obtained.
- Used for producing shapes which are extremely difficult to make like squares, D holes, splines, narrow slots, grooves and blended features.
- The absence of almost all mechanical forces makes it possible to machine fragile parts without distortion. In addition, fragile tools, wire can be used.
- It is also a good method for making deep holes in fuel injecting nozzles. Wire electrode of diameter ranging from 0.015 mm to 0.125 mm is used.
- Hydraulic valve spools are made using EDM.
- It is commonly used for thread cutting on jobs, drilling of micro-holes, helical profile drilling, curved hole drilling, re-sharpening of cutting tools and broaches, re-machining of die cavities without annealing, trepanning of holes with straight or curves axes.
- Delicate workpieces, such as copper parts for fitting into vaccum tubes, can be produced by this method. The workpiece in this case is too fragile to withstand the cutting force during conventional machining.
- EDM is used when repetitive parts are required, they can often be produced from the easy to make male electrode.
- EDM is used when machining accuracy must be maintained after heat treatment of the part. EDM is also used for metallurgical investigations.
- It is used for trepanning of rectangular holes in thin valve sleeves on curved surfaces

1.4 THEORY OF OPTIMIZATION

Optimization is essential for any problem that contains decision making, whether in engineering, mathematics, economics or any other field. The task of decision making means selecting between the various alternatives and our desire to make the "best" selection drives us to make the decision. The measure of goodness of the alternatives is described by an objective function or performance index. Optimization theory deals with selecting the best possible alternative for a given **objective** function. The area of optimization has received enormous attention in recent years, mainly because of the rapid progress in computer technology including the development and availability of user-friendly software and artificial neural networks. An example of this is the wide accessibility of optimization software tools such as the Optimization Toolbox of MATLAB and many other commercial software packages. There are various types of optimization methods, like Gradient descent optimization, Simulated annealing optimization, Particle swarm optimization etc. But for our present study, two optimization methods, namely "Single-objective optimization" and "Multi-objective optimization" are used.

1.4.1 Single-objective Optimization

Single-objective optimization refers to the process of finding the optimal solution for a problem with a single objective function. The objective is to find out the optimal combination of factors that maximizes or minimizes the response variable predicted by the response surface model independently.

The steps involved in single-objective optimization using RSM include:

- **Experimental Design:** Design and conduct a set of experiments to obtain data on the response variable for different combinations of input variables. The experimental design should be efficient and cover the relevant input variable space.
- **Response Surface Model Development:** Fit a response surface model to the experimental data using regression techniques such as linear regression, polynomial regression or other regression methods. The response surface model relates the input variables to the response variable and provides an equation or model that approximates the relationship.
- **Model Validation:** Assess the adequacy of the response surface model by checking for model fit, statistical significance and lack of fit. Validation ensures that the model

accurately represents the relationship between the input variables and the response variable.

- **Optimization Algorithm Selection:** Choose an appropriate optimization algorithm to search for the optimal values of the input variables based on the response surface model. Common optimization algorithms include gradient-based methods or derivative-free methods.
- **Objective Function Definition:** Define the objective function that quantifies the optimization goal, whether it is to maximize or minimize the response variable. The objective function is typically based on the predicted response values obtained from the response surface model.
- **Optimization Procedure:** Apply the selected optimization algorithm to iteratively search for the optimal values of the input variables that maximize or minimize the objective function. The algorithm adjusts the input variables according to a search strategy until convergence or the desired level of optimization is achieved.
- **Optimal Solution Evaluation:** Once the optimization algorithm converges, evaluate the optimal solution by simulating or testing it with the actual system or process. This step ensures that the predicted optimal values are feasible and can be practically implemented.
- **Sensitivity Analysis:** Perform sensitivity analysis to assess the robustness of the optimal solution and understand how variations in the input variables affect the response variable.

1.4.2 Multi-objective Optimization

Multi-objective optimization is applied to a problem that involves more than one objective function that are to be maximized or minimized. Thus, it involves finding the optimal combination of factors that simultaneously optimize the multiple responses predicted by the response surface models. A lot of steps involved in multi-objective optimization using RSM typically are same as that required for single-objective optimization. So, the further extra steps are only discussed below:

- **Multi-Objective Optimization Algorithm Selection:** Choose an appropriate multi-objective optimization algorithm to search for the optimal values of the input variables based on the response surface models. Common multi-objective optimization algorithms include genetic algorithms, particle swarm optimization, and evolutionary algorithms. These algorithms aim to find a set of solutions known as Pareto front, representing the trade-offs between the different objectives.

- **Optimization Procedure:** Apply the selected multi-objective optimization algorithm to iteratively search for the optimal values of the input variables that optimize the defined objective functions. The algorithm adjusts the input variables according to a search strategy and generates a set of solutions that represent the Pareto front.
- **Pareto Front Analysis:** Analyze the generated Pareto front to identify the trade-offs between the different objectives. Explore the solutions on the Pareto front to understand the relationship between the input variables and the multiple response variables and gain insights into the optimization problem.
- **Optimal Solution Selection:** Select the optimal solution from the Pareto front based on decision-maker preferences or additional criteria. The decision-maker can use subjective judgement, preference elicitation techniques or decision analysis methods to choose a solution that best suits the desired trade-offs between the objectives.

CHAPTER 2

LITERATURE REVIEW AND RESEARCH OBJECTIVES

2.1 LITERATURE REVIEW

In recent years, Inconel 718 is widely used in aerospace industry, oil and gas, and automobile due to their unique properties like hardness, strength, temperature and corrosion resistance properties. Though these material pose challenges during traditional machining due to their high work hardening tendency, poor thermal conductivity and chemical affinity towards the tool material. As a result rapid tool wear during the machining of Inconel 718 takes place. To overcome these challenges Electro Discharge machining on Inconel 718 is performed [1].

A case experimental research towards investigating aspects of Electro discharge machining (EDM) on Inconel 718 super alloy has been performed here. Based on three process variables viz. peak current, pulse -on duration and gap voltage experiments have been carried out to investigate their effects on various process performance features like Material removal rate(MRR), Surface crack density etc. Different types of surface irregularities have been found onto the surface of EDMed Inconel 718 [2]

Micro EDM process is capable of meeting Industrial requirements. Holes of small diameter were drilled on Inconel 718 using spark EDM process using tabular electrode. The experimental results showed that each process parameters influences at different levels on Material removal rate, hole taper and diameter overcut [3].

Electro Discharge machining (EDM) plays an important role in fabrication of micro-parts and structures such as micro-holes. Though due to the micro-discharge gap between electrode and workpiece, debris in the gap cannot be flushed away effectively during machining process. Debris accumulation can cause a poor machining stability and low production efficiency for micro-EDM. Compared to conventional EDM, MSSS EDM can be used to machinemicro-holes in Inconel 718 with a higher efficiency and quality because of its high response frequency of spindle. Recast layer can be improved using MSSS EDM due to a lower arc percentage under a higher response frequency. Recast layer is affected by single discharge energy and increase with increasing peak current and pulse on time [4].

Machining capabilities of modern EDM drilling machines for drilling cooling holes and diffusers in turbine blades are discussed. Experimental results of material removal rate, relative tool wear and surface integrity for EDM drilling and shaping processes. The EDM study proved experimentally that the recast layer can be reduced to the average thickness of 8 micrometer. Moreover the significant drawbacks of EDM which are low MRR and expensive tool manufacturing are overcome [5].

Deepak Rajendra Ununeet a1.[6] studied the micro-features on superalloy like Inconel 718,with dimensionally high accuracy using the process of Micro-electro-discharge drilling. Performence measures such as material removal rate(MRR), electrode wear ratio(EWR), overcut and taper angle are analysed as result of the micro EDM operation performed by choosing gap voltage, capacitance, electrode rotation speed(ERS) and vibrational frequency as control factors. An enhancement in the performance of low-frequency vibration assisted micro EDM due to improved flushing, debris evacuation and stable machining conditions is noticed. For the overall better performance of micro EDM while drilling Inconel 718, use of an optimum range of 40-50 Hz of low-frequency vibration is recommended.

Elena Bassoliet a1.[7] studies the paper reports on electro discharge drilling of small deep holes in Inconel 718.Process performances are measured with varying electrode size and geometry, attesting a pivotal effect of gap pollution on productivity and on the onset of a secondary detrimental removal of material by intergranular corrosion. The paper addresses Electro discharge drilling of small deep holes in Inconel 718, in the light of recent theories on the role of debris in the ignition of discharges. The observed effects of gap pollution include intergranular corrosion of the drilled surface, taking place in the conditions of low process efficiency.

S. Rajeshaet a1.[8] examined due to high creep-rupture strength and high fatigue endurance limit Inconel 718 is widely used in gas turbines, rocket engines, spacecraft structural components and also in nuclear power plant components. The most influential factors on MRR are the pulse current, duty factor and the interaction effect of both. Sensitivity control largely influences the MRR. Optimum setting of this parameter could result in better MRR with average surface quality. Surface finish while EDMing the inconel 718 is majorly influenced by pulse current, duty factor and gap control factors. Tool wear, thickness of the sputtered layer, and crack propagation on the tool were highly influenced by higher pulse current.

Bighnesh Kumar Sahuet a1.[9] investigated the aspects of Electro Discharge Machining on Inconel 718 super alloy using copper tool electrode. The objective of the current work is to investigate the effect of EDM parameters (Pulse-on time, peak current and gap voltage) on Material removal rate (MRR),Surface Crack Density, White layer thickness during Electro discharge machining on Inconel 718 super alloy using copper tool electrode. Different types of surface irregularities such as crater marks, pock marks, globule of debris have been found onto the surface of EDMed Inconel 718.It has been found from EDAX analysis that the carbon content has been increased on the EDMed work surface due to dielectric cracking.

M Manoharet a1.[10] examined Inconel 718 is one of the alloys that have relatively poor machinability in the conventional machining processes due to its work-hardening nature, retention of high strength at high temperature and low thermal conductivity. The surface roughness of the machined surface was measured and the nature of recast layer formed was evaluated and charecterized using scanning electron microscope. It is concluded that the adverse effects caused due to the erosion of flat profile electrodes on the machined surface could be overcome by employing convex profile electrodes.It is experimentally demonstrated that the effects of erosion of the flat profile electrode could be overcome by replacing it with the convex profile electrode.

Examined by Vitor Baldinet a1.[11] 65% used cemented carbide as cutting tool material,20% used ceramic cutting tools and 15% applied CBN tools. For EDM copper is the most used material as a tool electrode, followed by brass and graphite.The thickness of the white layer, varying from 3 to 50 micrometer, depends directly on the combination of the process parameters, which involves the variation of discharge current and pulse duration. The discharge energy generates different layers and characteristics on the workpiece surface, which influences the surface roughness, formation of white layer, micro-cracks, porosities and variation of surface hardness.

M. Kliuevet a1.[12] studied that Optimization of EDM machining strategies is permanently aimed to achieve the highest precision in minimal machining time, and therefore to reach better quality and higher efficiency. Correlation of the electrode wear pattern after EDM drilling with the geometry of the machined cavities is applied. Development and optimization of the diffuser machining strategy strengthen the position of EDM drilling to replace several elements of the process chain of turbine blade production by using one machine without reclaiming of the part.

Kevin Florio et a1.[13] studied that the energy distribution in EDM drilling is the factor that has to be analysed and optimized in order to achieve high performance machining, reduce costs and increase the quality of the machined parts. The present work proved the importance of deeper understanding and analysis of the fraction of energy in EDM process optimization, which can also be used in the development of the new generation of EDM machines since the energy fraction can be maximized on the workpiece side. The present work proved that the energy fraction going into the workpiece in EDM can vary substantially depending on different process conditions, such as discharge current and discharge duration.

Afzaal Ahmed et a1.[14] examined the unique combination of superior mechanical and chemical properties like hardness, strength, temperature and corrosion resistance is responsible for the extensive application of Inconel 718.The low thermal conductivity and high work hardening characteristics of Inconel 718 make it difficult to machine. In this study in order to select a suitable electrode material for the newly developed process, several experimental investigations have been conducted with three different electrode materials namely brass, copper and copper tungsten. Electrical and thermal properties of the tool electrode material have a significant effect on average surface roughness obtained.

The properties of the Inconel 718 superalloy are used in the manufacturing of aircraft components, its properties including high hardness and toughness cause machining difficulties when using the conventional method. Magdalena Machnoet a1.[15] observed that the nature of removing material using the EDM process causes the thermo physical properties of Inconel 718 to hinder its machinability. An experiment was conducted to evaluate the impact of five process parameters with a wide range of values on the process performance. Obtaining a high dimensional shape accuracy of holes has an enormous effect on their usability in the structure of the components in the aviation industry.

Oguzhan Yilmazet a1.[16] did his research work in which an automated and intelligent system was developed for EDM hole drilling operations on aerospace alloys namely Inconel 718.The developed system can be used to design EDM drilling process such as choosing optimal or best drilling parameters(discharge current, pulse on-time, pulse-off time and capacitance rate).Comprehensive experimental tests were designed and conducted for this purpose satisfying with essential precisions in hole making and accurate measurements. The input-output interactions have also been achieved via adaptive neuro-fuzzy inference technique that allows designing the drilling operations in an efficient, effective and reliable way.

Deepak G.Dilipet a1.[17] observed that drilling of cooling holes in turbine blades on difficult to machine materials like Inconel 718 has been one of the significant applications of micro EDM. In this study, optical non-contact 3D profilometry is used to characterize the side wall surface. Multi-objective optimization of the process parameters was carried out by the method of sum of weighted objectives using genetic algorithm. A machining strategy was proposed combining both response surface methodology and genetic algorithm to formulate an optimum cutting condition which was able to reduce the inner side wall surface roughness to 1.3587 micrometer. The predicted responses were validated experimentally and the maximum relative error obtained was less than 10%.

Electrical discharge machining (EDM) is one of the most efficient processes to produce high-ratio micro holes in difficult-to-cut materials in the Inconel 718 superalloy. Magdalena Machno et a1.[18] used response surface method (RSM) to develop models for optimization. Higher values of current amplitude, pulse time length and rotational speed of the working electrode resulted in higher drilling speed, lower linear tool wear, higher aspect ratio hole, lower holeconicity and lower side gap thickness at the hole inlet. This research also points to the learning potential of neural networks and the neural network models that guarantee a high match of the predicted values to the measured data.

M. Tanjilul et a1.[19] observed that EDM is a non-contact machining process that removes material through spark erosion and is often used for drilling holes in difficult-to-cut materials such as Nickel based super alloys. This study presents an innovative simultaneous flushing and vacuum assisted debris removal system, which facilitates better debris removal for deep-hole EDM drilling. The presented numerical model can be used to investigate the various factors influencing the removal of debries from the machining zone. Particle trajectories in deep hole EDM drilling can be successfully modelled by the proposed discrete phase modelling technique.

M. Kliuevet a1.[20] examined that for improving the process capability and machining efficiency of aerospace alloys, drilling of cooling holes and formation of diffusers can be combined into a single process by using the same electrode for both processes. Experimental results of material removal rate, relative tool wear and surface integrity for EDM drilling and shaping process are shown. The EDM study proved experimentally that the recast layer can be reduced to the average thickness of 8 micrometer. Concerning EDM drilling the erosion speed of 1.6 mm/sec is achieved through process parameter optimization by means of nonlinear regression and response surfaces.

P.Kuppanet a1.[21] reports on an experimental investigation of small deep hole drilling of Inconel 718 using the EDM process. The parameters such as pulse-on time, peak current, duty factor and electrode speed were chosen to study the machining charecterestics. Finally the parameters were optimized for maximum MRR with the desired surface roughness value using desirability function approach. The results obtained would be a good technical database for the aerospace or automotive manufacturers.

Mustafa Ay et a1.[22] used the gray relational analysis method to optimize the micro-electrical discharge machining drilling process of Inconel 718 nickle-based superalloy with multi performance characteristics. The hole taper ratio and hole dilation were the measured performences. A linear regression model was developed to estimate the performances. According to the gray relational grade coefficients, the pulse current has greater effect on multi performance characteristics than pulse duration parameter. The crack and damage characteristics of machined surfaces were reduced by decreasing the discharge current and shortening the pulse duration.

2.2 SCOPE AND OBJECTIVES OF THE PRESENT WORK

EDM has an extensive use in the manufacturing sector for machining a variety of materials including hard, tough, brittle, refractory, hard carbides, hardenable steels and exotic material provided it is electrically conductive. There are various reasons behind the selection of this process, and two of the most important are that it can be used to machine extremely hard materials so distortion of the workpiece due to heat treatment can be eliminated, and the second one is it gives good accuracy and high repeatability. The other reasons include that, no cutting forces are involved so thin andfragile materials can be machined and also any complicated shapes can be made on the tool can be reproduced on the workpiece. EDM gives good surface finish, surface finish of 0.8-3.0 micrometer can be achieved. Also time of machining is less than conventional machining. EDM machining produces chip/burr free work surfaces. Thus, the scope of work in the field of electro discharge machining is very high.

2.2.1 Objectives of the Present Work

A lot of research has been carried out on electric discharge machining by considering the effects of several factors on the different responses. However, small work has been done on the effect of four factors on the different responses. So, keeping in mind previous research works and the current necessity in the study of electric discharge machining on Inconel 718, the aims of the current work are as follows:

- To conduct the experiments on the EDM setup and analyze the process on Inconel 718.
- To identify the effects of various process parameters such as peak current, pulse-on time, pulse-off time, gap voltage on the material removal rate(MRR) and surface roughness by performing the response surface methodology (RSM).
- To perform the optimizations in order to get the optimal values of the factors for the predicted desired values of the responses.

CHAPTER 3

EXPERIMENTAL SETUP

3.1 EDM MACHINE SYSTEM

The photographic view of the experimental setup used in the present research work is shown in the figure below.

Fig 3.1 Experimental Setup of EDM machine system

3.3 COMPONENTS OF ELECTRIC DISCHARGE MACHINING SYSTEM

An experimental setup for Electric Discharge Machining(EDM) typically involves few key components and subsystems. Here is a detailed description of the components and their functions:

1.<u>Power Supply:</u> Power generator is one of the most important parts of an EDM system. The primary function of the power generator is to convert an alternating (AC)to pulsed direct current. DC is used to produce the unidirectional spark discharges between the gap of the tool and work. Power supply has a solid state rectifier circuit to convert AC to DC and a pulse to generate DC pulses or unipolar pulses. A fraction of DC power is used to generate a square wave signal with the help of digital multi-vibrator oscillator. The pulsing unit is of four different types:

a) Rotary impulse generator

b) Relaxation generator

c) Pulse generator

d) Hybrid generator

2.<u>Dielectric system:</u> It consists of fluid, reservoir, filters, pump and delivery devices. A good dielectric fluid should possess the following properties

1. It should have high dielectric strength, that is electrically non-conductive until the required breakdown voltage between electrodes is obtained.
2. Take minimum possible time to break down, that is, ignition delay time once the breakdown voltage is reached.
3. Deionise the gap immediately after the spark has occurred.
4. Serve as an effective cooling medium
5. Have high degree of fluidity
6. To carry away the removed metal and graphite particles.

Dielectric may be fed into the working area either by pressure or by vacuum suction. The dielectric has to be filtered in order to remove the metal and graphite particles. Fluids commonly used are transformer oil, paraffin oil, kerosene, lubricating oils and de-ionized water.

3.Electrode and Workpiece: Material used as tool electrode should have the following properties:

a) It should be easily maintainable

b) It should have low wear rate

c) Easily available and cheap

d)It should have high electrical conductivity

e) It should have high thermal conductivity

f)It should have high density and high melting point

g) Easily Manufacturable.

The following are the different electrode materials

1.Graphite 2.Electrolytic oxygen-free copper 3.Telluriam copper 4.Brass

4.Servo system: It is used to maintain a predetermined gap between gap between tool and the workpiece. Too large gaps will prevent the formation of sparks. If the gap is very small there will be short circuit, which will damage both the tool and work.

The basic requirement of electrode feed controls are:

- In EDM both, the workpiece and tool are eroded and therefore feed control must maintain a movement of electrode towardsthe workpiece at such a speed that the working gap, and hence the sparking voltage remains same.
- Hunting of the mechanism is not allowed because the gap is small.
- Overshooting of the mechanism may short circuit and damage both tool and work.
- Low inertia drive is required for rapid response of the mechanism.
- It should have rapid reversing speed with no backlash.

5.Frame: Nearly all the machines are of vertical C type construction. It consists of a base, a column and head. The coordinate table which supports the workpiece is usually mounted on the base. Machines with fixed work table are also available at a lower cost.

6.Pump/Intensifier: The pump or intensifier is an important component of the EDM setup which is responsible for pressuring the EDM oil to the desired level. The pump is typically powered by an electric motor. The intensifiers may have different designs and configuration based on the specific requirements and applications.

CHAPTER 4

DESIGN OF EXPERIMENT

In the field of statistics and research, the design of experiment (DOE) is defined as a systematic approach of planning, conducting, analyzing and interpreting the possible outcome of an experiment by considering the input process parameters at different levels. It is an efficient method that enables us to study the relationship between factors (input variables) and responses (output variables), thus helping in the optimization of process parameters with the help of which we can take data driven decisions. This information is useful for building statistical methods to predict the process performance. Thus it defines the specific setting levels of the combinations of elements at which the different runs in the experiments are to be done.

In statistics a full factorial experiment is an experiment whose design consists of two or more factors each at different possible levels and whose experimental design takes all possible combinations of these levels across such factors. Such experimental designs allow researchers to examine both the main effect and the interaction effect on the response variable. Thus this design provides a comprehensive understanding of how different factors interact with each other and impact the response variable.

If the number of combinations in a full factorial design is too high, then a fractional factorial design may be considered in which some of the combinations can be omitted. For example, say, if there are 9 factors at two levels then 2^9=512 combinations would be generated. It is not feasible to perform such a large number of experiments due to high cost or resource constraints. In such cases, fractional factorial designs may be used. These designs select a subset of factor combination to be tested, providing information about the main effects and some interaction effects while reducing the number of experimental runs. But this design is less attractive if a researcher wishes to consider more than two levels. Attempts are made to employ the full factorial design of experiments and analysis of variance approach for studying the influence of process parameters on output response parameters.

4.1 HISTORY OF DESIGN OF EXPERIMENT

The history of DOE can be traced back to the early 20th century when statisticians and scientists recognised the need for a more efficient and structured approach to experimentation. However, in the year the 1920s and 1930s,Ronald A. Fisher, a British statistician invented the design of experiments at the Roth Amsted Experimental Station which was located 25 miles north of London. He made significant contributions to the development and popularization of DOE and his work laid the foundation for modern DOE. The most well-known of a group of Japanese scientists, Genichi Taguchi, is known for his quality-improvement techniques. Toyota was one of the firms to implement Taguchi techniques. Some basic concepts of the design of experiments were described by Ronald A. Fisher and those fundamental principles are

- **Randomization:** Random assignment is the process of assigning individuals at random to groups or to different groups in an experiment, so that each individual of the population has the same chance of becoming a participant in the study.
- **Replication:** It involves running multiple independent experimental runs or observations for each treatment combination with identical experimental conditions. It helps in estimating the experimental error, assessing the variability, and obtaining more precise and reliable results. When the noise comes from uncontrollable nuisance variables, replication improves the signal-to-noise ratio.
- **Blocking:** Blocking is the non-random arrangement of experimental units into groups(blocks) consisting of units that are similar to one another. Blocking reduces known but irrelevant sources of variation between units and thus allows greater precision in the estimation of the source of variation under study.
- **Orthogonality:** Orthogonal designs are those in which the effects of different factors are uncorrelated or independent of each other. It thus helps in the efficient estimation of the main effects and interaction between factors.They help in obtaining clear and unambiguous information about the effects of individual factors on the response variable.

4.2 APPLICATIONS OF DOE

DOE finds applications in various fields, including manufacturing, engineering, healthcare, agriculture, and social sciences. Some common uses of DOE include:

- **Process optimization:** DOE helps identify the critical process factors that affect the outcome of a process and determine the optimum levels for these factors, thus optimizing the manufacturing processes. By systematically varying the factors and measuring the response, researchers can uncover the optimal settings that lead to improved product quality, efficiency or cost savings.
- **Product development:** DOE is used to optimize product formulations or designs by studying the effect of various factors, such as materials, design parameters, or production methods, on the final products quality or performance. This helps in creating better products with reduced development time.
- **Quality improvement:** DOE can be employed to identify the critical process parameters and their optimal settings that have the most significant impact on product quality. By reducing variability and understanding the impact of different factors, organisations can enhance product reliability and consistency, reduce defects, and ensure satisfaction.
- **Root cause analysis:** When troubleshooting a process or system, DOE can be used to systematically investigate the potential causes of a problem. By varying the factors suspected of contributing to the issue, researchers can determine the root cause and develop appropriate solutions.
- **Sensitivity analysis:** DOE allows for the evaluation of the sensitivity of the process or system to different factors. By systematically varying the factors, researchers can assess which one have the most significant impact and focus resources on those that matter the most.
- **Robustness testing:** DOE helps in testing the robustness of a process or product design by intentionally introducing variations in operating conditions or component specifications. This helps in identifying the range of conditions within which the process or product performs reliably.
- **Cost optimization:** DOE aids in optimizing costs by identifying the key factors that contribute to cost variations and determining their optimal levels. This helps in achieving cost savings without sacrificing quality or performance.
- **Scientific research:** In scientific studies, DOE helps researchers investigate hypotheses, explore relationship between variables, and determine cause and effect relationships. It allows for controlled experimentation, reducing bias and confounding factors and enabling more reliable conclusions.

4.3 TAGUCHI METHOD APPROACH TO DESIGN OF EXPERIMENTS

Taguchi methods are a set of statistical technique for improving the quality and performance of products and processes by optimizing the design parameters. They are based on the philosophy of Genechi Taguchi, a Japanese engineer who pioneered the concept of robust design.

Here's an overview of the Taguchi Method approach to the design of experiments.

1. Define the process objective, or more specifically, a target value for a performance measure of the process. This may be a flow rate, temperature etc. The target of a process may also be a minimum or maximum. The deviation in the performance characteristics from the target value is used to define the loss function for the process.
2. Determine the design parameters affecting the process. Parameters are variables within the process that affect the performance measure such as temperature, pressures etc. The number of levels that the parameters should be varied at must be specified. Increasing the number of levels to vary a parameter at increases the number of experiments to be conducted.
3. Create orthogonal arrays for the parameter design indicating the number of and conditions for each experiment. The selection of orthogonal arrays is based on the number of parameters and the levels of variation for each parameter and will be expounded below.
4. Conduct the experiments indicated in the completed array to collect data on the effect on the performance measure.
5. Complete data analysis to determine the effect of the different parameters on the performance measure.

L9 and L16 Array: It is a statistical tool suggested by G Taguchi. L9 is an orthogonal array which can be used to conduct experiments involving typically 4 factors set at 3 levels. In L9 it has 9 trails or runs that are recorded with each factor (process parameter) set at different level. Using the recorded data, S/N ratio (signal to Noise ratio) is computed and Graphs are plotted to select the optimal factor level settings. In L16 it has 16 trails or runs that are recorded with each factor set at different level.

Signal-to-noise ratio (S/N ratio): One of the key parameters used in quality control is the signal-to-noise ratio (S/N). Which measures a product's quality by comparing the desired signal with the noise or unwanted variation output. The S/N ratio is an integral part of the Taguchi. The Taguchi method is a statistical technique that uses the S/N ratio to optimize product design and manufacturing processes. Signal-to-noise ratio is a measure of robustness which can be used to identify the control factor settings that minimize the effect of noise on the response. MINITAB calculates a separate signal-to-noise ratio for each combination of control factor levels in the design. For static designs, Minitab provides four S/N ratios: Smaller is better, Larger is better, and two Nominal is best ratio.

Larger is better

The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the larger-is-better S/N ratio using base 10 log is:

$S/N = -10*\log(\sum(1/Y^2)/n)$ -- (Eq. 1)

Where Y = responses for the given factor level combination

n = number of responses in the factor level combination.

Smaller is better

The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the smaller is better S/N ratio using base 10 log is:

$S/N = -10*\log(\sum(Y^2)/n)$ --(Eq. 2)

Where Y = responses for the given factor level combination

n= number of responses in the factor level combination

Nominal is best

The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the nominal-is-best (1) S/N ratio using base 10 log is:

$S/N = -10*\log(s^2)$ -- (Eq 3)

Where s = standard deviation of the responses for all noise factors for the given factor level combination.

CHAPTER 5

EXPERIMENTAL PLAN AND PROCEDURES

5.1 EXPERIMENTAL PLAN

The present experimental study has been performed as per the following plan:

- One work specimen of Inconel 718 with size of 100*100*1 mm are taken to perform the experiment.
- Arrangement for experimental setup is required to perform the Electric Discharge machining.
- A mechanical clamping device is used to keep the work specimen at the desired position.
- First a Trial experiment is conducted and it is made sure that Final experiment can be started.
- Conducted Electric Discharge machining using four process parameters namely peak current, pulse-on time, pulse-off time, Gap voltage. The machining is conducted using proper combinations of input process parameters.
- Observe and measure the diameter of machined blind holes by using a vernier calliper.
- Machining time is noted with the help of stopwatch.

5.2 WORK AND TOOL MATERIAL

In the present research work, one work specimen of Inconel 718 with size of 100*100*1 mm is taken to perform the experiment.

5.2.1 Inconel 718

Inconel 718 is a precipitation-hardenable nickel-chromium alloy containing also significant amounts of iron, niobium and molybdenum along with lesser amounts of aluminium and titanium. It combines corrosion resistance and high strength with outstanding weldability including resistance to postweld cracking. The alloy has excellent creep rupture strength at temperatures to 1300 degree F or 700 degree centigrade. Because of having above mentioned properties it is widely used in aerospace, gas turbines, rocket motors, spacecraft, space shuttles, nuclear reactors, pumps, turbo pump seals, and tooling. The mechanical and thermal properties of Inconel 718 is given in Table 5.1

Fig 5.1 Work Specimen

Table 5.1: Mechanical and thermal properties of the Inconel 718

Property (Unit)	**Value**
Tensile Strength (MPa)	965
Thermal Conductivity(W/m-k)	6.5
Melting Point (Degree C)	1370
Density (gm/cc)	8.19
Young’s modulus (GPa)	29.8

5.2.2 Tool Material

Copper is widely used as a tool material due to its excellent favourable properties. Copper is a chemical element that is also a metal. Its key properties are that it has excellent electrical conductivity, high thermal conductivity and good corrosion resistance. It is also ductile and has an interesting reddish-brown colour. The combination of these properties leads to the wide application of copper for engineering and aesthetic uses. Its physical and chemical properties are given in Table 5.2.

Table 5.2: Physical and Chemical properties of Copper

Properties (Unit)	**Values**
Hardness (HV)	107
Melting point (Degree C)	1085
Specific Gravity	8.95
Density	8.96

5.3 EXPERIMENTAL DETAILS

5.3.1 Selection of Process Parameters

Four independently controllable process parameters, namely: Peak current, pulse-on-time, pulse-off-time, Gap voltage are considered as input parameters to carry out the experiments.

5.4 EXPERIMENTAL PROCEDURE

Table 5.3: Experimental Data

Sl. No.	Voltage (V)	Peak Current(A)	Ton (sec)	Toff (sec)	W/P weight Before(g)	W/P weight After(g)	Tool weight Before(g)	Tool weight After(g)	Time (min)
1	40	10	20	10	42.1275	42.0120	22.4276	22.4112	2:12:69
2	40	14	30	15	41.8937	41.7852	22.3788	22.3700	1:36:68
3	40	18	50	20	41.7852	41.6581	22.3620	22.3545	1:25:47
4	60	10	30	20	41.6581	41.5345	22.3545	22.3487	2:00:99
5	60	14	50	10	41.5345	41.4185	22.3487	22.3425	1:36:19
6	60	18	20	15	41.4185	41.3262	22.3425	22.3311	0:58:71
7	80	10	50	15	41.3262	41.2144	22.3311	22.3245	1:51:57
8	80	14	20	20	41.2144	41.1062	22.3245	22.3212	1:18:13
9	80	18	30	10	42.0120	41.8945	22.4112	22.3885	1:27:90

Following a review of the literature and the machine’s feasibility, a trial experiment was conducted, and process parameters and their ranges were identified. Then a specimen of Inconel 718 is cut into 2 specimens each of size 100*50*1 mm^3 by performing Electric Discharge machining. Now, by using the design matrix of DOE, the experiment was conducted by varying the input parameters at all levels and values of the responses were noted down.

5.5 MEASURING EQUIPMENT

In this section, the equipment which is used to measure the values of the desired responses using the machined workpiece is discussed here. The MRR and Tool wear rate are to be measured.

5.5.1 Measuring Microscope

A measuring microscope is a magnification based instrument tool used to measure parts or samples. They can vary greatly in both capability and automation, but sometimes they are manual. The value of using measuring microscope over an optical comparator is the resolution of the image. With a higher resolution image, better accuracy can be guaranteed, so measurement quality greatly improves. For the LM-1100,it has sub-micron level accuracy in high precision mode, this is great for small parts with tight tolerances. The accuracy of a measuring microscope is generally better than an optical comparator, but it varies based on model and capability. Different types of measuring microscope are available to match different applications. Recent models of measuring microscopes are able to instantly measure dimensions without XY stage movement or focusing, enabling the measurement of many objects in a short amount of time.

5.5.2 Measuring Microscope Specifications:

Effective Magnification	50X (up to 1000X Available)
Vision	Binocular
Working Distance	34 mm
Working Throat	100 mm
Stage	XYZ High Precision Stage
Travel (X,Y & Z)	100x200x100 mm
Resolution	0.00005”/0.001 mm

Fig 5.2 Measuring Microscope

5.5.3 Weighing Machine

Weighing balances are instruments which are used to determine the weight or mass of an object. It is available in a wide range of sizes with multiple weighing capacities. They areessential tools in laboratories, commercial kitchens and pharmacies and many more uses. Precision and analytical balances are specific types of weighing balances which measure much smaller masses than the average scale. An analytical balance is the most precise because it has higher readability, measuring to the nearest 0.0001g. Analytical balances usually include draught proof weighing chambers for precise measuring of mass and are often used alongside anti-vibration tables to increase accuracy.

Fig 5.3 Weighing Machine

5.6 MEASUREMENT OF MRR

Material removal rate is the volume of material removed per unit time during Electric Discharge machining. The material removal rate is calculated by this following equation.

MRR=(W1-W2)*1000/(p*t) --(Eq. 1)

Where W1 and W2 are the weight of workpiece before and after machining respectively (grams), p is the density of workpiece in (gm/cc), t is the machining time in minutes.

5.7 MEASUREMENT OF TOOL WEAR

TWR is expressed as the ratio of the difference of weight of the tool before and after machining to the machining time.

TWR=(Wtb-Wta)/t --- (Eq. 2)

Where Wtb=Weight of the tool before machining, Wta=Weight of the tool after machining, T=Machining time.

5.8 MEASUREMENT OF OVERCUT

Overcut is the difference between the hole diameter and the wire diameter divided by two.

OC= (Djt-Dt)/2-- (Eq. 3)

Where, Djt= diameter of hole produced in the workpiece, Dt= Diameter of tool

CHAPTER 6

EXPERIMENTAL INVESTIGATION AND ANALYSIS OF RESPONSES

This chapter includes an experimental observation or the results of the experiments and the influence of process factors on the responses. This chapter analyses the observed data for mathematical modelling, response surface plots and optimization. The link between the process parameters and responses is established by developing the Taguchi optimization using statistical software. Moreover, the optimization is also performed to know the optimal values of the factors at the desired predicted values of the responses, which will also help in the validation experiment.

6.1 EXPERIMENTAL RESULTS

The procedure for the selection of appropriate process parameters and the development of design matrix for the experiment using MINITAB software have been outlined. The Electric Discharge machining experiment is performed for the correct combinations of input process parameters as designed by Taguchi method.

Table 6.1: Input and Output Parameters

Ex No.	Voltage (Volt)	Peak Current (Amp)	Pulse On-time (sec)	Pulse Off-time (sec)	MRR (mm^3/min)	TWR (mm^3/min)	Overcut (mm)	Circularity
1	40	10	20	10	6.410	0.832	0.1245	0.942
2	40	14	30	15	8.279	0.614	0.1	0.884
3	40	18	50	20	10.928	0.589	0.164	0.868
4	60	10	30	20	7.545	0.324	0.0995	0.861
5	60	14	50	10	8.852	0.432	0.135	0.887
6	60	18	20	15	11.464	1.294	0.0835	0.928
7	80	10	50	15	7.378	0.380	0.116	0.865
8	80	14	20	20	10.162	0.283	0.1125	0.883
9	80	18	30	10	9.826	1.73	0.0995	0.917

6.1.1 Analysis of Material Removal Rate(MRR)

Table 6.2: Response Table for Signal to Noise Ratios

Level	Voltage	Peak Current	Pulse on-time	Pulse off-time
1	18.42	17.02	19.15	18.31
2	19.23	19.15	18.59	18.97
3	19.12	20.60	19.02	19.49
Delta	0.80	3.59	0.57	1.18
Rank	3	1	4	2

Table 6.3: Response Table for Means

Level	Voltage	Peak Current	Pulse on-time	Pulse off-time
1	8.539	7.111	9.345	8.363
2	9.287	9.098	8.550	9.040
3	9.122	10.739	9.053	9.545
Delta	0.748	3.628	0.795	1.182
Rank	4	1	2	3

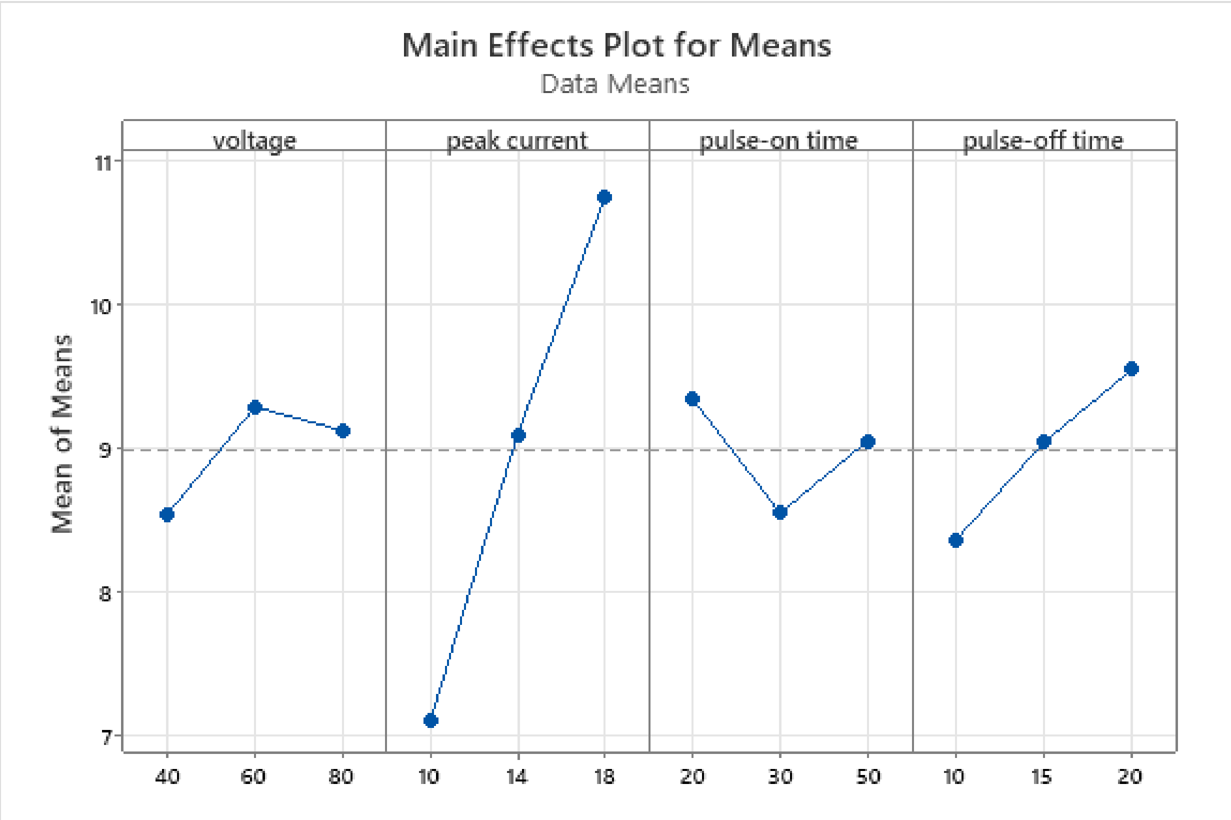


Fig 6.1 Main Effects plot for Means

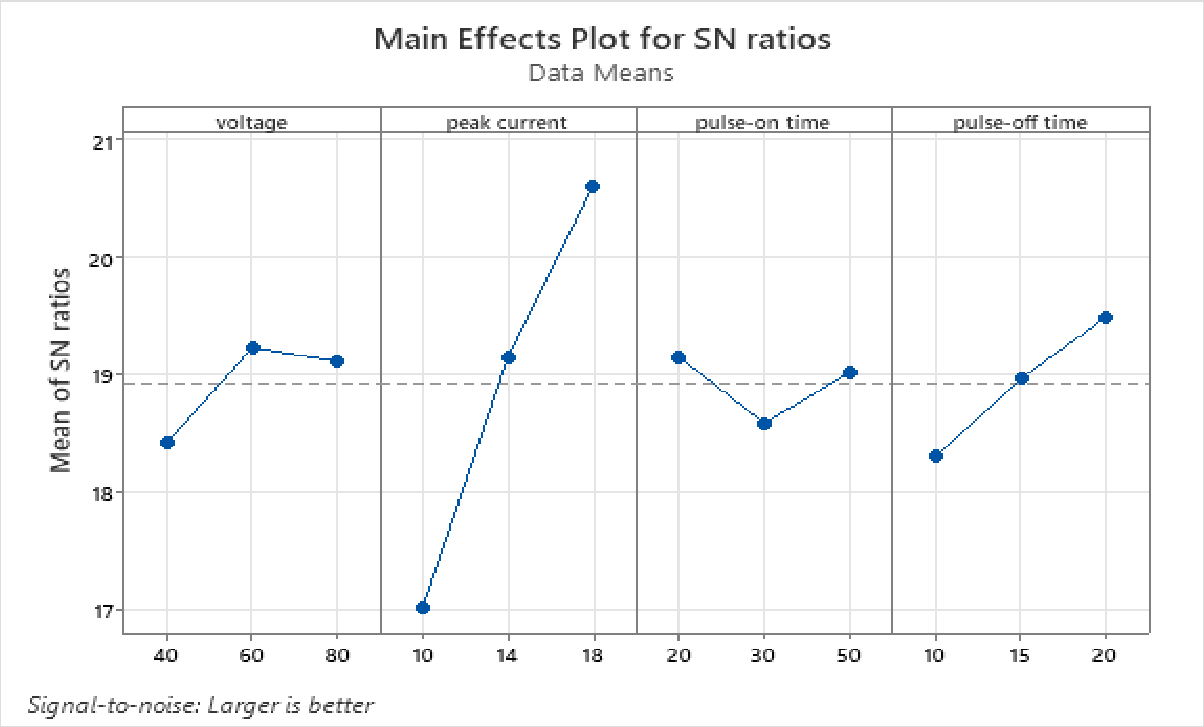


Fig 6.2 Main Effects plot for SN ratios

6.1.2Effects of Process Parameters on MRR

As the current increases, each individual spark removes a larger crater of metals from the workpice. The net effect is an increase in MRR. Some effect is also observed when spark voltage is raised. A decrease in MRR with increase in pulse duration is attributed to unsteady machining conditions observed for pulses greater than 20 microseconds. Keeping all the factors constant increasing in breakdown voltage will result in increase in energy per spark. Therefore, MRR also increases. Apart from current and Voltage, the electrode area for a given setting has influence on the rate of metal removal. As the machining area increases MRR increases to a maximum value and then decreases again. As the current density increases MRR also increases. As the voltage increased, for the same current density we get higher MRR.

6.1.3 Analysis of Tool Wear Rate(TWR)

Table 6.4: Response Table for Signal to Noise Ratios

Level	Voltage	Peak Current	Pulse on-time	Pulse off-time
1	3.4773	6.5970	3.4410	1.3756
2	4.9469	7.4971	3.0883	3.4674
3	4.8692	-0.8006	6.7658	8.4504
Delta	1.4696	8.2977	3.6758	7.0747
Rank	4	1	3	2

Fig 6.3 Main Effects plot for Means

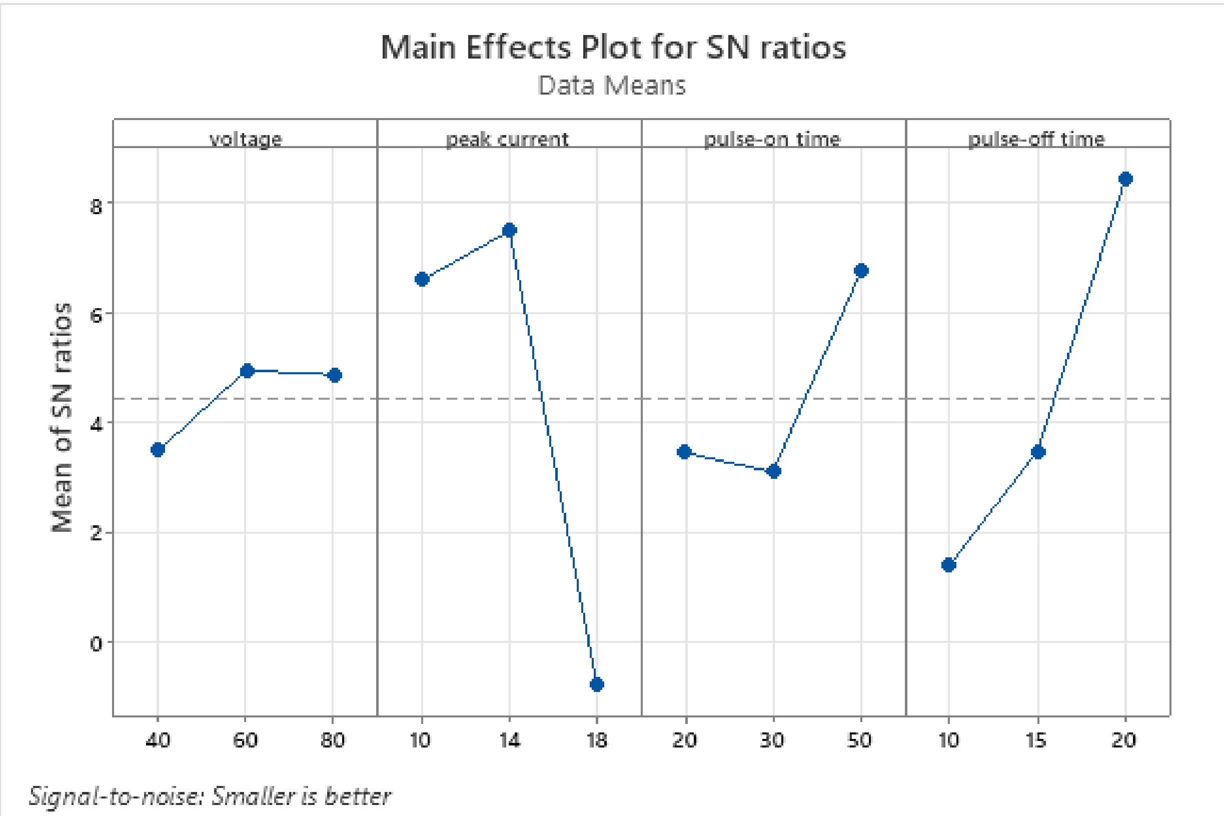


Fig 6.4 Main Effects plot for SN ratios

Table 6.5 Response Table for Means

Level	Voltage	Peak Current	Pulse on-time	Pulse off-time
1	0.6783	0.5120	0.8030	0.9980
2	0.6833	0.4430	0.8893	0.7627
3	0.7977	1.2043	0.4670	0.3987
Delta	0.1193	0.7613	0.4223	0.5993
Rank	4	1	3	2

6.1.4Effects of process parameters on Tool Wear Rate(TWR)

In case of copper electrode with negative polarity for the specified conditions, there seems to be a pulse duration for which relative electrode wear is negative due to metal deposition.

The plasma channel diameter in EDM varies along the gap with time. It has been reported that major part of the tool erosion occurs during the fast few microseconds of pulse. Hence the use of a pulse with a low initial current could reduce the tool wear.

If the current increases the tool wear rate also increases. If the voltage increases the tool wear rate decreases.

6.1.5 Analysis of Overcut

Table 6.6: Response Table for Signal to Noise Ratios

Smaller is better

Level	Voltage	Peak Current	Pulse on-time	Pulse off-time
1	17.93	18.95	19.55	18.51
2	19.67	18.79	20.03	20.09
3	19.24	19.10	17.27	18.24
Delta	1.73	0.31	2.76	1.85
Rank	3	4	1	2

Table 6.7: Response Table for Means

Level	Voltage	Peak Current	Pulse on-time	Pulse off-time
1	0.12950	0.11333	0.10683	0.11967
2	0.10600	0.11583	0.09967	0.09983
3	0.10933	0.11567	0.13833	0.12533
Delta	0.02350	0.00250	0.03867	0.02550
Rank	3	4	1	2

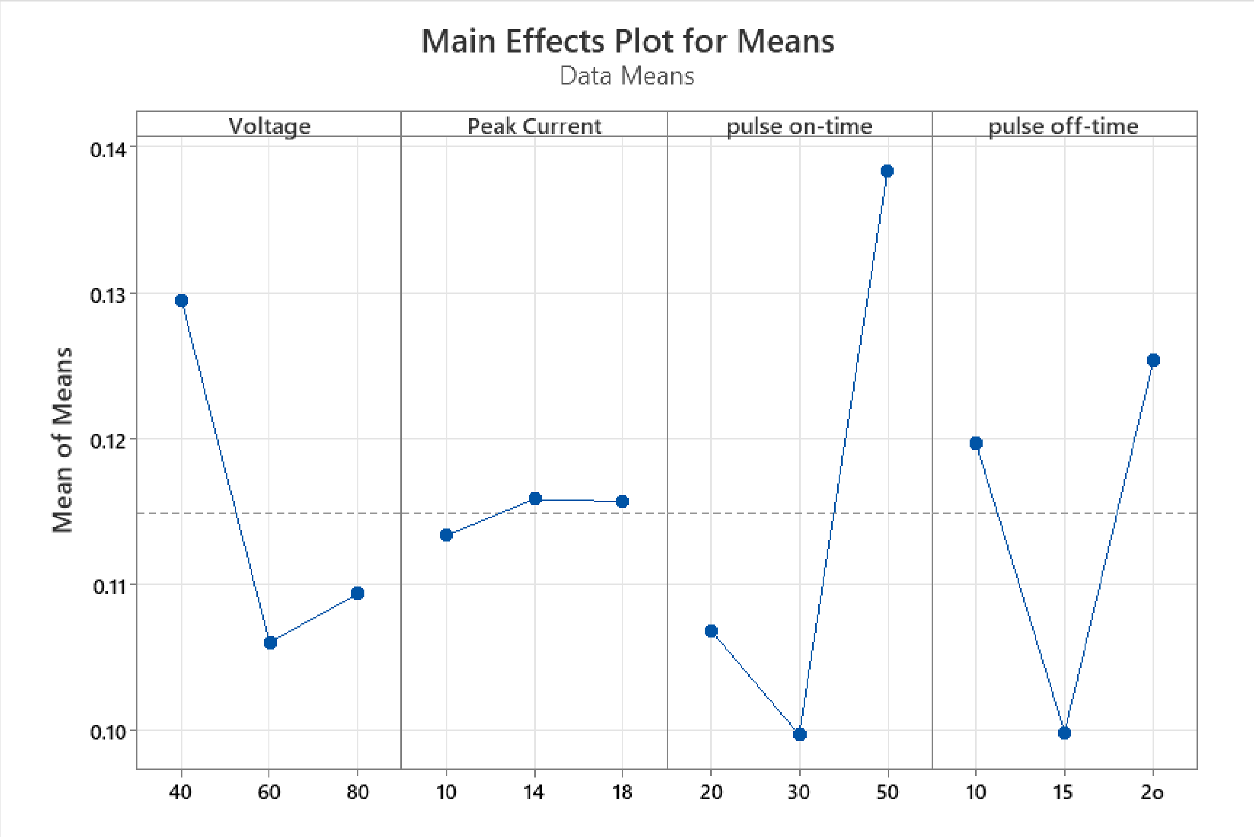


Fig 6.5 Main Effects plot for Means

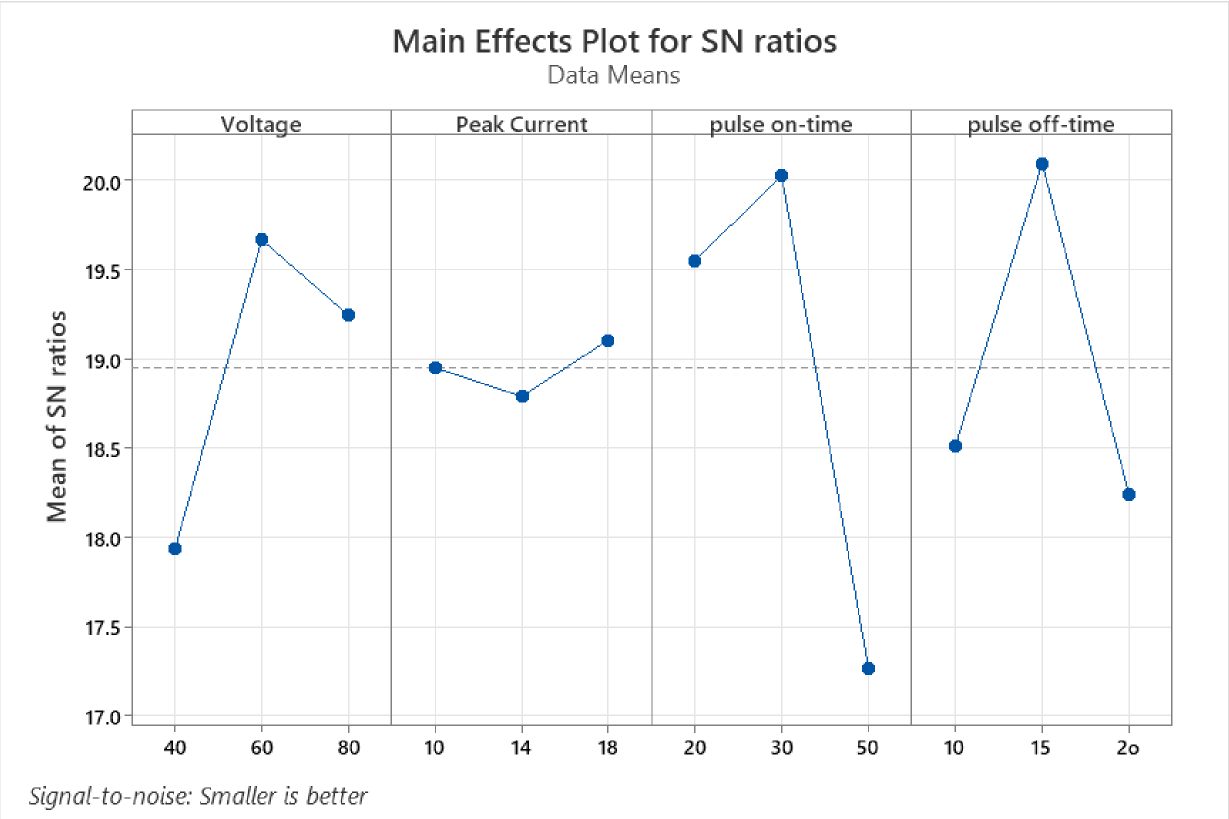
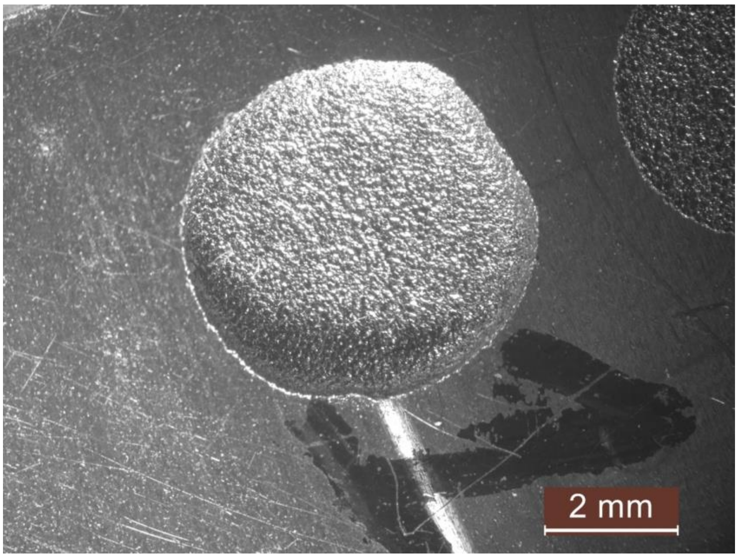


Fig 6.6 Main Effects plot for SN ratios



Microscopic View of EDMed Hole

6.1.6Effects of Process Parameters on over cut

Taguchi method is used to analysis the result of response of machining parameter for smaller is better criteria. The analysis of the responses indicate that the interaction factors Ton x Dia and Ton x It is not significant for over cut and the value of Ip is most influencing of OC and also Dia. of tool is significant. The case of OC Smaller is better so from the study it is clearly definite that It is the most important factor then dia. of the tool and last is Ton. The over cut between the dimension of the electrode and the size of the hole is inherent to the EDM process which is unavoidable though adequate compensation is provided in the tool design. To achieve the accuracy minimization of overcut is essential. The over cut are effect to each parameter such as diameter of tool, discharge current and pulse-on time. The main effect plot for S/N ratios shown in graph for over cut.

6.1.7 Analysis of Circularity

Table 6.8: Response Table for Signal to Noise ratios

Larger is better

Level	Voltage	Peak Current	Pulse on-time	Pulse off-time
1	-0.9398	-1.0262	-0.7496	-0.7710
2	-0.9968	-1.0644	-1.0412	-0.9932
3	-1.0310	-0.8771	-1.1769	-1.2034
Delta	0.0912	0.1873	0.4273	0.4324
Rank	4	3	2	1

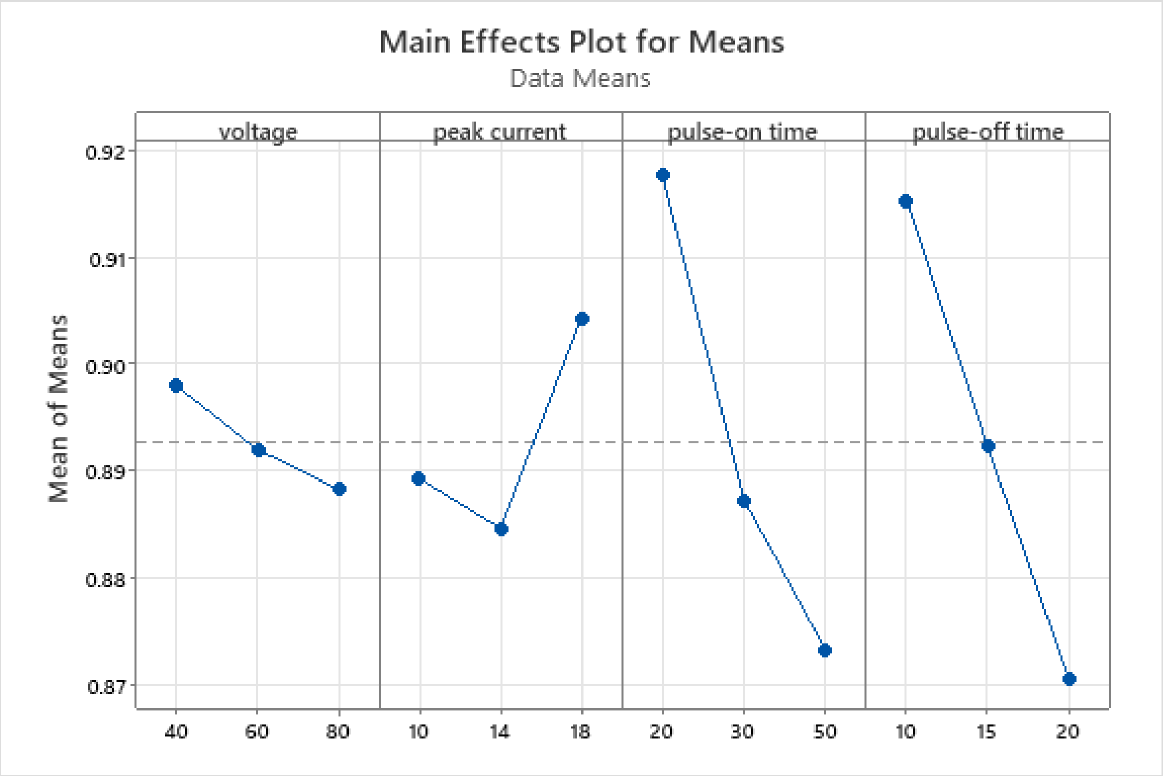


Fig 6.7 Main Effects plot for Means

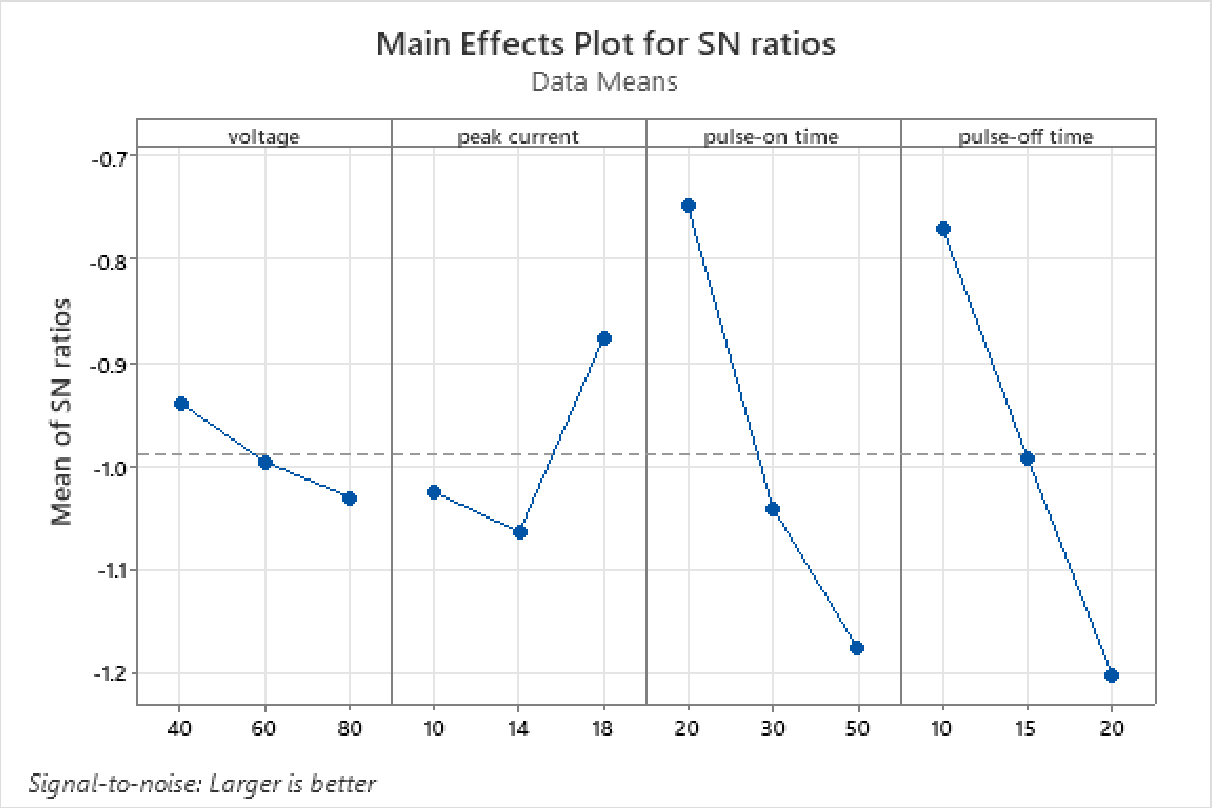


Fig 6.8 Main Effects plot for SN ratios

Table 6.9: Response Table for Means

Level	Voltage	Peak Current	Pulse on-time	Pulse off-time
1	0.8980	0.8893	0.9177	0.9153
2	0.8920	0.8847	0.8873	0.8923
3	0.8883	0.9043	0.8733	0.8707
Delta	0.0097	0.0197	0.0433	0.0447
Rank	4	3	2	1

6.1.8 Effects of Process Parameters on circularity

There are few input parameters which plays significant role on Circularity. The input parameters are Voltage, Peak Current, Pulse-on time and Pulse-off time which have influences on Circularity. It has been observed that Circularity decreases with increase of Voltage. Circularity first decreases then increases with the increase of Peak Current. It has been observed that with increase in pulse-on time and Pulse-off time Circularity decreases. To achieve the accuracy maximization of Circularity is essential. The main effect plot for S/N ratios shown in graph for Circularity.

6.2 OPTIMIZATION OF PROCESS PARAMETERS

In this part, the effort has been made to optimize Material removal rate(MRR), Tool wear rate(TWR), Overcut and Circularity for the Electric Discharge Machining of Inconel 718.Single-objective optimization and multi-objective optimization are used to optimize the process parameters so that we can get the desirable value of the responses.

6.2.1 Optimization of MRR

In the present study, single-objective optimization of MRR has been carried out for the electric Discharge machining of Inconel 718.Here our aim is to maximize the material removal rate(MRR).

MINITAB software has been used to obtain the optimum MRR response in electric discharge machining of Inconel 718.In the S-N graph it has been observed that MRR is maximum at voltage 60 volt. So the optimum voltage for which MRR is larger is 60 volt.
In S-N graph it has been observed that MRR is maximum at peak current 18 Amp. So the optimum peak current for which MRR is larger is 18 Amp.

Also it has been noticed that in S-N graph MRR is maximum at pulse-on time 20 sec and at pulse-off time 20 sec. So the optimum pulse-on time and optimum pulse-off time for which MRR is larger are 20 sec and 20 sec respectively.

6.2.2 Optimization of TWR

In the present study, Single-objective optimization of TWR has been carried out for the electric discharge machining of Inconel 718. Here our aim is to minimize the Tool Wear rate(TWR).

MINITAB software has been used to obtain the optimum TWR response in electric discharge machining of Inconel 718. In the S-N graph it has been observed that TWR is minimum at voltage 40 Volt. So the optimum voltage for which TWR is smaller is 40 volt.

In S-N graph it has been observed that TWR is minimum at peak current 18 Amp.So the optimum peak current for which TWR is smaller is 18 Amp.

Also it has been noticed that in S-N graph TWR is minimum at pulse-on time 30 sec and at pulse-off time 10 sec. So the optimum pulse-on time and optimum pulse-off time for which TWR is smaller are 30 sec and 10 sec respectively.

6.2.3Optimization of Overcut

In the present study, Single-objective optimization of Overcut has been carried out for the electric discharge machining of Inconel 718. Here our aim is to minimize the Overcut.

MINITAB software has been used to obtain the optimum overcut response in electric discharge machining of Inconel 718. In the S-N graph it has been observed that Overcut is minimum at voltage 40 volt. So the optimum voltage for which Overcut is smaller is 40 volt.

In S-N graph it has been observed that Overcut is minimum at peak current 14 Amp. So the optimum peak current for which Overcut is smaller is 14 Amp.

Also it has been observed that in S-N graph Overcut is minimum at pulse-on time 50 sec and at pulse-off time 20 sec. So the optimum pulse-on time and optimum pulse-off time for which Overcut is smaller are 50 sec and 20 sec respectively.

6.2.4 Optimization of Circularity

In the present study, Single-objective optimization of Circularity has been carried out for the electric Discharge machining of Inconel 718. Here our aim is to maximize the Circularity.

MINITAB software has been used to obtain the optimum Circularity response in electric discharge machining of Inconel 718. In the S-N graph it has been observed that Circularity is maximum at voltage 40 volt. So the optimum voltage for which Circularity is larger is 40 volt.

In S-N graph it has been observed that Circularity is maximum at peak current 18 Amp. So the optimum peak current for which Circularity is larger is 18 Amp.

Also it has been noticed that in S-N graph Circularity is maximum at pulse-on time 20 sec and at pulse-off time 10 sec. So the optimum pulse-on time and optimum pulse-off time for which Circularity is larger are 20 sec and 10 sec respectively.

6.2.5 Multi-objective Optimization

Gray relational analysis

The application of Taguchi method in mechanical engineering is generally intended to identify the optimal combination of processing parameters in accordance with single quality characteristics. However, EDM is a machining process with four objectives: High MRR, Low Tool Wear Rate, Low Over-cut and high Circularity. Under multi-objective requirements, the factor levels of Taguchi analysis often oppose one another, therefore we combined Taguchi method with gray relational analysis in order to obtain optimal parameter combinations capable of meeting multiple objectives. Gray relational analysis is performed as follows:

In the use of gray relational analysis to obtain an optimal combination of parameters in accordance with multiple objectives, an operation is applied to the experimental data of quality characteristics, the results of which are then used to calculate the gray relational grades of the sequences for ranking. In gray relational analysis, the factors in factor set P(x),which forms a factor space, can be written as a sequence: $x_i = (x_i(1), x_i(2), x_i(3), \ldots x_i(m))$, where x_i belongs to P(x), in which i= 1, 2, 3 ……. n. Furthermore, $x_i(k)$, in which k= 1, 2, 3, ….. m, denotes the elements constituting the factor sequence. To make the sequences compareable and achieve the objective of grayrelational analysis, the S/N ratios of the multiple objectives (MRR, TWR, Over-cut and Circularity) must be normalized. A higher S/N ratio indicates a better gray relational coefficient and is thus processed as a higher-is-better charecteristics. Higher-is-better normalization can be defined as follows:

$X_I(k)= (X_i(K)-\min\{X_i(K)\}) / (\max[X_i(K)]-\min[X_i(K))$----------------------------------(Eq. 1)

Where $X_i(K)$ is the value of quality characteristic k and $\max[X_i(K)]$ and $\min[X_i(K)]$ indicate the maximum and minimum values of attribute k in a sequence respectively.

The ultimate objective in the application of gray relational analysis is to obtain the gray relational grades between sequences, thereby illustrating the importance of a given sequence in relation to a reference sequence. The average of the grey relational coefficients is the gray relational grade, and the ranking based on the magnitude of the gray relational grades is referred to as the gray relational order. The current parameters settings are voltage of 40 volt, peak current of 18 Amp, pulse-on time of 20 sec and pulse-off time of 20 sec for achieving the predicted maximum value of MRR of 11.464mm^3/min, minimum value of Tool wear rate of 0.283 mm^3/min, minimum value of Overcut of 0.0835 mm and maximum value of Circularity of 0.942.

6.3 FINAL VERIFICATION EXPERIMENTS

To verify the proposed mathematical models, four experiments have been carried out according to the parameter settings obtained from the optimization result for the maximum material removal rate, minimum tool wear rate, minimum overcut and maximum circularity and all the responses together. These experimental results have been compared with the predicted optimum results of the responses and percentage errors in prediction are found. It was observed that the predicted value is quite close to the experimental result which is desirable.

Table 6.10: Final verification experiments

Responses	**Parameter Settings**	**Experimental results**	**Predicted Results**	**%Error in prediction**
Maximum MRR (mm^3/min)	Voltage 60 volt, Peak current 18 amp, pulse-on time 20 sec, pulse-off time 20 sec	14.009	11.464	22.19

Responses	Parameter Settings	Experimental results	Predicted Results	%Error in prediction
Minimum tool wear rate (mm^3/min)	Voltage 40 volt, Peak current 18 Amp, Pulse-on time 30 sec, Pulse-off time 10 sec	0.2634	0.283	6.93
Maximum Circularity	Voltage 40 volt, Peak Current 18 Amp, Pulse-on time 20 sec, pulse-off time 10 sec	0.908	0.942	3.61
Minimum Overcut	Voltage 40 volt, Peak Current 14 Amp, Pulse-on time 50 sec, pulse-off time 20 sec	0.0785	0.0835	5.99

CHAPTER 7
CONCLUSION AND FUTURE SCOPE OF WORK

7.1 CONCLUSION

The present research carried out is an attempt to study and understand the effect of electric discharge machining on Inconel 718.The principle objective of the present investigation is to understand the influence of different control parameters variation on the material removal rate and tool wear rate.Based on the experimentation and investigations carried out,the following conclusions can be drawn

- The Taguchi method models that have been developed are adequate and can be used to accurately predict the responses for a set of parameters.
- Finding the result of MRR discharge current is most influencing factor and then pulse duration time and the last is diameter of the tool. MRR increased with the discharge current. As the pulse duration extended, the MRR decreases monotomically.
- In the case of Tool wear rate the most important factor is discharge current then pulse on time and after that diameter of tool.
- In the case of overcut the most important factor is discharge current then diameter of the tool and no effect on pulse on time.

7.2 Future Scope of Work

The existing study gives more emphasis on the failure prediction and its eradication. A follow-up study can be conducted to extend the proposed monitoring system to predict and control the surface integrity in real time. Such a system can double up as an online inspection system for the machined components. Also, further analysis can be conducted on the dependency of material properties on the discharge characteristics. Since the problem of arcing is common to every electric discharge machining process, the proposed monitoring system can be further extended to other varieties of EDMs.

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