Experimental Investigation Of Machining Characteristics Of Titanium Alloy (Ti-6Al-4V) By Using EDM Process

A Dissertation submitted
in partial fulfillment of the requirements
for the degree of

Master of Engineering
in
Production Engineering

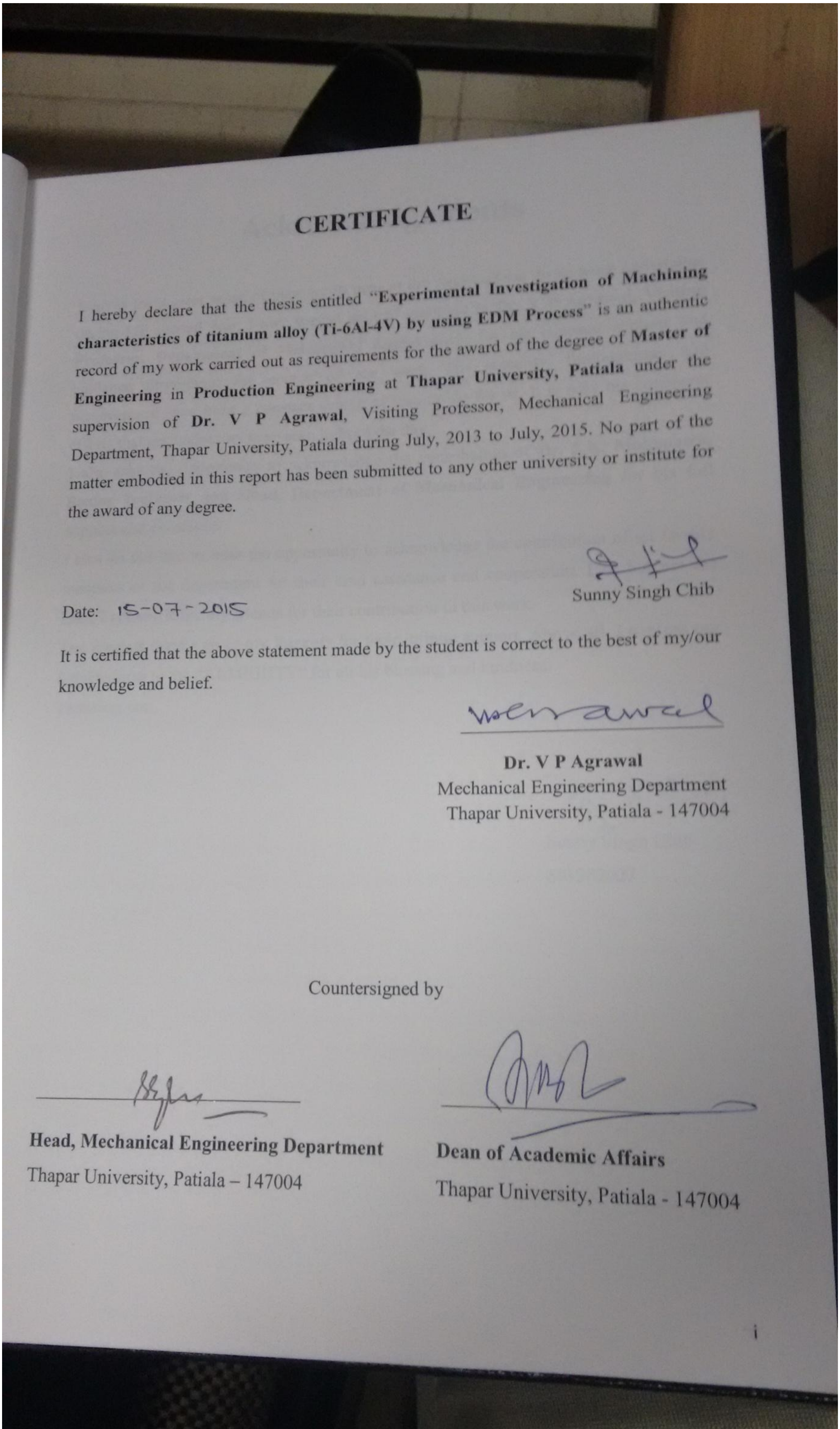
by

Sunny Singh Chib
Roll No. 801382027

Under the Supervision of
Dr. V P Agrawal
Visiting Professor

MECHANICAL ENGINEERING DEPARTMENT
THAPAR UNIVERSITY, PATIALA

July, 2015



CERTIFICATE

I hereby declare that the thesis entitled "**Experimental Investigation of Machining characteristics of titanium alloy (Ti-6Al-4V) by using EDM Process**" is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering** in **Production Engineering** at **Thapar University, Patiala** under the supervision of **Dr. V P Agrawal**, Visiting Professor, Mechanical Engineering Department, Thapar University, Patiala during July, 2013 to July, 2015. No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

Sunny Singh Chib

Date: 15-07-2015

It is certified that the above statement made by the student is correct to the best of my/our knowledge and belief.

Dr. V P Agrawal
Mechanical Engineering Department
Thapar University, Patiala - 147004

Countersigned by

Head, Mechanical Engineering Department
Thapar University, Patiala – 147004

Dean of Academic Affairs
Thapar University, Patiala - 147004

Acknowledgements

It gives me a great sense of pleasure to present the report of the thesis work undertaken during ME second year. I owe special debt of gratitude to **Dr. V P Agrawal, Visiting Professor, Department of Mechanical Engineering**, for his constant support and guidance throughout the course of our work. His sincerity, thoroughness and perseverance have been a constant source of inspiration for us. It is only his cognizant efforts that our endeavors have seen light of the day.

I also take the opportunity to acknowledge the contribution of **Dr. S.K. Mohapatra, Senior Professor and Head, Department of Mechanical Engineering** for his full support and assistance.

I also do not like to miss the opportunity to acknowledge the contribution of all faculty members of the department for their kind assistance and cooperation. Last but not the least, I acknowledge my friends for their contribution in this work.

The greatest thanks go to my **Parents** for their infinite support. Above all, I express my indebtedness to the “ALMIGHTY” for all his blessing and kindness.

Thanking you.

Sunny Singh Chib
801382027

Abstract

With the invention of super alloys such as titanium based super alloys, nickel based super alloys, carbides, stainless steels, hastelloy, nitralloy, etc., increases the need of non-traditional manufacturing processes. These materials are so hard and tough that they can-not be machined by conventional machining processes. Such materials finds a large variety of applications, especially titanium based super alloys where high strength to weight ratio and hardness is required. The materials which fulfill the modern industry's demand are very difficult to machine. Non conventional machining methods have been developed to control the machining problem.

Electrical discharge machining (EDM) is the most commonly used method among the new machining methods. It is widely used because of its capability to process difficult to machine materials and intricate shapes. It can modify the surface properties such as roughness and hardness of different materials by changing the electrode material and also by mixing different powders in the dielectric. Powder mixed electric discharge machining is the latest innovation for increasing the machining capabilities.

Ti-6Al-4V is the material with unique properties like high strength to weight ratio, corrosion resistance, high temperature strength, weld and fabricability makes it most attractive material. Due to its applicability in different industrial application like in aerospace, marine etc., selected for thesis purpose along with copper as electrode and kerosene as dielectric. As Ti-6Al-4V has low electrical conductivity so graphite and copper powders has been mixed with dielectric fluid. Three factors at three levels each i.e. peak current, pulse-on time and different powder mixed dielectric has been choosen to investigate the effect of powder on output responses. The output responses are material removal rate (MRR), tool wear rate (TWR), surface roughness (R_a) and micro-hardness. In this thesis work, Taguchi method has been applied to design the experiments by adopting an appropriate orthogonal array, so that study can be conducted with minimum possible number of experiments. The experiments have been performed as per as L27orthogonal array. ANOVA is the main statistical tool used to analyze results both analytically as well as graphically, by indicating the percentage contribution of each factors on all output responses. From the experimental results it is found that material removal rate, surface roughness and micro-hardness increases with the addition of powders. Material removal rate, tool wear rate, surface roughness and micro hardness were also optimized in the study and the optimal value of each of the above response was calculated using their signal to ratio values. Grey relation analysis has been used to unearth the best result for different outcomes of the EDM process.

Keywords: EDM, Taguchi design, PMEDM, Orthogonal Array, Grey Relation Analysis.

Contents

LIST OF FIGURES

LIST OF TABLES

Nomenclature

T_{ON} =Pulse-on time

T_{OFF} =Pulse-off time

Y = Grey relation coefficient

N_i = Normalization of various responses of experimental trial

N = total number of experiments

$\bar{m}$ = Average response of different experiments trials

μ_{opt} = Desired mean value

V_e = Variance of error

X_{ij} = Response value at different experiment trials

R_a =Surface roughness

Greek Symbols

Δ = Absolute difference between N_{oj} and N_{ij}

µ =Micron

% =Percentage

Acronyms

ANOVA = Analysis of Variance

DOE =Design of experiments

DOF = Degree of freedom of a factor

MRR =Material removal rate

TWR =Tool wear rate

RSM =Response surface methodology

mm =millimetre

mg =milligram

min =Minute

s =second

CHAPTER 1

INTRODUCTION

Machining is a process which involves the removal of some material from the work piece (machining allowance) so that a specific geometry can be produced at a definite degree of accuracy and surface quality. The machining processes may be either subtractive manufacturing or additive manufacturing. Parts are manufactured by casting, forming, and by various shaping processes often require further operations before they are made available for end use or assembly. In many engineering applications, many parts have to be interchangeable in order to function properly and reliably during their expected service lives. High accuracy and precision increases efficiency of an equipment. This requires a high degree of dimensional accuracy and surface finish of the parts during manufacturing. This dimensional accuracy and surface finish of the parts during manufacturing can-not be maintained by using traditional machining methods. Because traditional machining methods are often ineffective in machining those parts which actually requires close tolerances. In order to cope up with these challenges, new processes have been developed. These new processes play a considerable role in the aircraft, automobile, tool, die, and mold making industries. Generally machining methods are classified as according to the number of machining actions causing the removal of material from the workpiece.

- Traditional Machining
- Non- traditional Machining

1.1 Traditional Machining

Machining is a process which removes certain material from work pieces to change them to final parts of required shape and size by controlling material removal process. Traditional or conventional machining uses a tool which is harder than the workpiece to be machined. This tool should be penetrated in the workpiece to a certain depth. A relative motion between the tool and workpiece is responsible for forming or generating the required shape. The absence of any of these elements in any machining process such as the absence of tool-workpiece contact or relative motion makes the process a nontraditional. Traditional machining can be classified according to the machining action of cutting (C) and mechanical abrasion (MA) [20]

1.2 Non-traditional Machining

Non-traditional machining processes are musty used to produce geometrically complex and precision parts for well known industries like aerospace, electronics and automotive manufacturing. There are many multiple geometrically designed precision parts, such as deep internal cavities, miniaturized microelectronics and fine quality components that can be manufactured only by nontraditional machining processes. The greatly improved thermal, chemical and mechanical properties of the new engineering materials made it impossible to machine them using the traditional machining processes of cutting and abrasion. As in traditional machining processes material is removed from workpiece by using tools that are harder than the workpiece. For example, the high ratio of the volume of grinding wheel worn per unit volume of metal removed (50–200) made classical grinding suitable only to a limited extent for production of polycrystalline diamond (PCD) profile tools. The high cost of machining ceramics and composites and the damage generated during machining are major obstacles to the implementation of these materials. In addition to the advanced materials, more complex shapes, low-rigidity structures, and micro-machined components with tight tolerances and fine surface quality are often needed [20].

1.3. Classification of non-conventional machining processes:-

Non-Conventional Machining processes are classified according to the type of energy used for the machining of the work materials and are as:-

1.3.1 Mechanical Processes:-It removes the material by using mechanical forces of abrasive particles for material removal.

- **Ultrasonic machining (USM):-** It is also known as ultrasonic impact grinding. This process is most suitable for non conducting materials. It is a process in which material is removed from the workpiece by using a vibrating tool oscillating at ultrasonic frequencies. This process used to remove hard and brittle materials by using an axially oscillating tool at ultrasonic frequencies [18–20 kilohertz (kHz)]. During that oscillation, the abrasive slurry is continuously flows into the machining zone between a soft tool (brass or steel) and the workpiece. The abrasive particles hammered into the workpiece surface and cause chipping of fine particles from it. The oscillating tool, at amplitudes ranging from 10 to 40 μm, imposes a static pressure on the abrasive grains and feeds down as the material is removed to form the required tool shape.[19,20,22].It differs from most other machining operations as very little heat is produced. The tool never comes in contacts with workpiece. Therefore grinding pressure is rarely more than 2 pounds, which makes this process perfect for machining extremely hard and brittle materials, such as glass, sapphire, ruby, diamond, and ceramics.[21] Machine time depends upon the frequency at which the tool is vibrating, the grain size and hardness, and the viscosity of the slurry fluid. Hardness of grain must be equal or greater than the hardness of the workpiece. Commonly B_4C or SiC are used, because of their hardness [25].

- **Water jet machining (WJM):-**In this process high velocity water jet is used to cut the workpiece. Water jet travels at very high velocity ranging as high as 900 m/s i.e. approximately Mach 3. When the stream strikes a workpiece surface, the erosive force of water removes the material rapidly. During this process kinetic energy of water is converted into pressure energy. This pressure energy induces the erosive forces for cutting. In this water acts as a saw and cuts a narrow groove in the workpiece material [20].
- **Abrasive jet machining (AJM):-** it is also known as abrasive micro-blasting or pencil blasting or micro-abrasive blasting. In this process material removal takes places due to impingement of fine abrasive particles. These particles move with a high speed gas stream towards the work surface. When these particles strike the work surface, they cause small fractures, and the gas stream carries both the abrasive particles and the fractured particles away. The sizes of abrasive particles are of 0.025mm in diameter. The gas is discharges at a pressure of few atmospheres. The most commonly used abrasive materials are aluminum oxide (corundum) and silicon carbide at small grit sizes. The grains should have sharp edges and should not be reused as the sharp edges are worn down and smaller particles can clog nozzle. Abrasive Jet Machining is used for deburring, etching, and cleaning of hard and brittle metals, alloys and nonmetallic materials (e.g., germanium, silicon, glass, ceramics, and mica). The jet velocity is in the range of 150-300 m/s and pressure is from two to ten times atmospheric pressure [21][27]. It is used to cut intricate shapes or to form specific edge shapes.

1.3.2 Chemical processes:-

It removes the material by the action of chemicals on workpiece material.

- **Chemical machining (CHM):-** It is the controlled dissolution of workpiece material by means of a strong chemical reagent. In this process material is removed from workpiece by immersing it in a chemical reagents or etchants; such as acids and alkaline solutions. Material is removed by microscopic electrochemical cell action, which results in corrosion or chemical dissolution of a metal. This controlled chemical dissolution will simultaneously etch all exposed surfaces even though the penetration rates of the material removal may be only 0.0025–0.1 mm/min.

The basic process takes many forms:-

- **Electrochemical machining (ECM):-** It is a electro-chemical non-traditional machining process in which material is removed through electrolysis. It is reverse of electroplating. It uses the electrochemical dissolution (ECD) phase to remove material from workpiece in order to give machining allowance by using ion transfer in an electrolytic cell.
- **Chemical blanking:-**It is also known as chemical milling (CHM) or photochemical machining (PCM), also called chemical blanking (PCB). It uses a chemical dissolution action to remove material from workpiece in order to give machining allowance by using ion in an etchant and used for etching through thin sheets [22].
- **Photochemical machining (PCM):-** It is used for etching, where weak chemical reagents are used for polishing or deburring and chemical jet machining where a single chemically active jet is used [21].

1.3.3 Thermal processes:-

These processes remove the material by melting or vaporizing the workpiece material. Many secondary phenomena relating to surface quality occur during machining such as micro-cracking, formation of heat-affected zones, and striations.

- **Electron beam machining (EBM):-** It is an electro-thermal non-traditional machining process in which high speed electrons are impinged on workpiece so that its kinetic energy is transferred to workpiece, thereby producing intense heating effect which futher remove material by melting and vaporization [19]. The electron beam can be focused on a point upto a diameter of 10-200 μm. With the help of high voltage, very high velocity can be obtained. The power density can go upto 6500 billion W/mm^2. Therefore it is a very controlled vapourization process. Very fine and narrow holes upto diameter of 25-120 μm can be drilled. . EBM can be used for very accurate cutting or boring of a number of metals. Surface finish is better and kerf width is narrower than those for other thermal cutting processes.

- **Ion beam machining (IBM):-** It is a non-conventional machining process used in which a stream of accelerated ions is used to remove the atoms from the surface of the workpiece. The ions of inert gas such as argon are accelerated by electrical means in a vacuum in order to remove, add or modify atoms on the surface of the workpiece. The ejected ions are directed to form a beam. The ions are mono-energetic having velocities in order of 1km/s. The beam removes atoms from the work piece by transferring energy and momentum to atoms on the surface of the work piece. When an atom strikes a cluster of atoms on the work piece, it removes approximately 0.1 and 10 atoms from the work piece material. It is used for micro fabrication and nano fabrication. IBM finds its applications in accurate machining of any material. It is used in the semiconductor industry, manufacturing of aspheric lenses, texturing surfaces to increase bonding, for producing atomically clean surfaces on devices such as laser mirrors and for modifying the thickness of thin films and membranes.
- **Laser beam machining (LBM):-** It is an electro-thermal non-traditional machining process in which electrical energy is used to generate laser beam and thermal energy of laser beam is used for material removal. Laser beam can be easily focused by using optical lenses. Its wavelength ranges from half micron to 70 microns. A laser beam may have power more than 1MW/mm^2. It uses the light energy of a laser beam to remove material by vaporization and ablation. There are many types of lasers such as Helium- Neon laser, CO_2 laser, Argon-ion laser, Nd:YAG laser etc. But most commonly used in LBM are the carbon dioxide (CO_2) gas lasers. Lasers produce collimated monochromatic light with constant wavelength. The laser beam can be focused on any spot of much smaller diameter and of high intensity. The light rays are parallel; so that photon does not diverse from parallel path. The light produced by the laser has significantly less power than a normal white light, but it can be focused on a very small spot thus produces a light of higher intensity, so very high temperature in a localized area can be

produced for material removal [19]. Lasers are widely used for a no: of industrial applications, such as heat treatment, welding, measurement and for a number of cutting operations such as drilling, slitting, slotting, and marking operations. Very small diameter holes up to 0.025 mm can be drilled very easily. Larger holes can be drilled by controlling the outline cut of the hole [23]. This process can be used to machine a variety of material including metals with high hardness and strength, soft metals, ceramics, glass, plastics, rubber, cloth, and wood [20].

- **Electrical discharge machining (EDM):-** It is an electro-thermal non-traditional machining process where electrical energy is used to generate electrical spark and thermal energy of spark is used for material removal [19].

1.4 Electrical discharge machining(EDM)

It is an electro-thermal non-traditional machining process where electrical energy is used to generate electrical spark and thermal energy of spark is used for material removal. Electrical discharge machining (EDM) is one of the most primitive non-traditional machining processes. EDM process is based on thermoelectric energy produced between the work piece and an electrode [25].EDM process uses electrical energy which further generates a channel of plasma between the cathode and anode, and turns it into thermal energy. The thermal energy generates a channel of plasma between the cathode and anode. The temperature generated in this process is in the range of 8000–12,000 ºC [16]. When the pulsating direct current power supply occurring between 20,000 and 30,000 Hz is turned off, the plasma channel breaks down. This causes a sudden reduction in the temperature allowing the circulating dielectric fluid to implore the plasma channel and flush the molten material from the workpiece surface in the form of microscopic debris [2].

The advanced materials have some eye-catching properties such as high strength, high bending stiffness, good damping capacity, low thermal expansion, better fatigue characteristics makes them potential material for robustic use. Such type of materials finds application in modern industrial world. Present manufacturing industries are facing challenges from these advanced materials like super alloys, ceramics, and composites, which are hard and difficult to machine, requiring high precision, high accuracy and good surface quality which increases machining cost [19].To meet these challenges new advanced manufacturing processes, needs to be developed. With conventional machining processes advanced materials are often very difficult to machine, due to certain improved thermal, chemical and mechanical properties of new advanced materials. Conventional machining such as turning, milling and drilling etc. are ineffective in machining these advanced materials. So it results in poor materials removal rate, excessive tool wear and increased surface roughness [20].

Electrical discharge machining (EDM) is most commonly used manufacturing technology in the industry application. This method is proved wonder for modern manufacturing industry and gained great publicity. This method can be applied to machine both electric conductive and semi-conductive materials. It is a non-contact method so materials can be machined irrespective of certain properties such as their hardness, shape and toughness. Therefore many hard-to-cut and brittle materials can be inexpensively processed by EDM. This process is widely used to produce dies, punches and moulds, finishing parts for aerospace and automotive industry and surgical components [1]. It is used to machine difficult to-machine materials and high strength temperature resistant alloys. Very difficult geometries and highly delicate parts are effectively machined by this process [17].

Many modification of this technique have been developed, such as sinking EDM, wire EDM, EDM milling and micro-hole EDM drilling etc. A large number of dielectrics are used during EDM process. Generally hydrocarbon oil based and water based dielectric fluids are used in EDM machining processes. But, with the development of this technology, gaseous dielectrics are also brought in use. These gaseous dielectrics are more environmental friendly and more economical. So these are attracting more and more attentions from researchers [4]. For receiving higher material removal rates and less electrode wear, a number of powders are mixed with dielectrics.

1.4.1 History of EDM:-

In 1770, the English chemist Joseph Priestly discovered the erosive effect of electrical discharges or sparks on metals. In 1940 two Russian scientists, Dr. B.R. Lazarenko and Dr. N.I. Lazarenko harvested this idea and applied in their research. During Second World War, they were assigned with a project by the Soviet government in order to investigate the wear caused by sparking between tungsten electrical contacts, because wear was a big problem for the maintenance of automotive engines. Researchers found that the sparks were more uniform in oil than in air. In 1943 they made first spark erosion machine, which were capable to erode hard metals such as tungsten or tungsten carbide. The spark generator used by them is known as the Lazarenko circuit, which has been employed over many years in power supplies for EDM machines and proved to be used in many current applications.

The Lazarenko EDM system uses resistance capacitance type of power supply; it was used in EDM machine till 1950's and then acted as the model for successive development in EDM. Due to the poor quality of electronic components, the performances of the machines were not very impressive. In the 1960's, the advancement of semiconductor industry leads to significant modernization of EDM machines. During this era die-sinking machines became reliable and produced quality controlled surfaces with accuracy, but wire-cutting machines were still at their very beginning. During the subsequent decades, great improvements were made in generator design, process automatization, servo-control and robotics. The use of pulse and solid state generators solved existing problems with weak electrode as well as the inventions of orbiting systems. In the 1970's the number of electrodes is reduced to create cavities. In 1980's Computer numerical controlled (CNC) EDM was developed in USA [25].

In 1990's fuzzy logic control, neural networks, response surface methodology, Taguchi optimization etc. are some new methods were used to control EDM process, that increases applied basic EDM [16].

1.4.2 Types of EDM processes:-

- **Sinking EDM**:- In this process electrical energy is converted into thermal energy through a series of discrete electrical sparks taking place between the electrode and workpiece. EDM process uses electrical energy which further generates a channel of plasma between the cathode and anode, and turns it into thermal energy. The thermal energy generates a channel of plasma between the cathode and anode. The temperature generated in this process is in the range of 8000–12,000 [16]. When the pulsating direct current power supply occurring between 20,000 and 30,000 Hz is turned off, the plasma channel breaks down. This causes a sudden reduction in the temperature allowing the circulating dielectric fluid to implore the plasma channel and flush the molten material from the workpiece surface in the form of microscopic debris. Workpiece and electrode is dipped into dielectric fluid in order to avoid the oxidation. Cavity formed on the surface of workpiece is a mirror image of tool shape. In sinking EDM electrode material is copper, brass, graphite, tellurium copper etc. The gap between workpiece and electrode, movement of electrode in different axes and pulse generator is controlled by numerical control. The dielectric liquid is filtrated to remove debris particles [2].

- **Wire EDM:**-Wire-cut EDM (WEDM) is the most popular machaining process. It has capability to machine conductive, exotic and high strength and temperature resistive (HSTR) materials, in order to generate intricate shapes and profiles. Material from workpiece is removed by a series of discrete sparks taking place between the work piece and the wire, which is separated by a stream of dielectric fluid. Wire is continuously fed to the machining zone by a micro-processor eliminating the need for elaborate reshaped electrodes, which are essential in the conventional EDM [16]. A thin copper wire of diameter about 0.1 to 0.3 mm is used as the electrode and the workpiece is mounted on a CNC controlled worktable. Wire cut EDM machine is capable to cut complex two dimensional shapes on workpiece in X-Y axis. Its movement is controlled CNC controlled worktable. [2]. Wire EDM process is widely used in tool and die-making industry, in the fields of medicine, electronics and the automotive industry [35].
- **Micro EDM:**-Micro-EDM is used to machine micro-holes and micro-shafts. This process is also capable to machine very small diameters upto 5µm and very complex three-dimensional (3D) micro cavities.

  Micro EDM process is basically of four types:-

  a) Micro-wire EDM: - In micro-wire EDM, a wire is used to cut a workpiece which has a diameter as small as to 0.02 mm.
  b) Die-sinking micro-EDM: - In die-sinking micro-EDM, an electrode having micro-features is used to cut its mirror image in the workpiece.
  c) Micro EDM drilling: - In micro EDM drilling, micro-electrodes having diameters as small as 5–10 µm are used to ‘drill’ micro-holes in the workpiece.
  d) Micro-EDM milling: - In Micro-EDM milling, micro- electrodes having diameters as small as 5–10 µm are used to produce 3D cavities by adopting a similar procedure as that in conventional milling.
- **Powder Mixed EDM:**-This is a new technique which increases material removal rate by adding some suitable material in form of powder is mixed with the

dielectric fluid of EDM. Powder mixed EDM enhancement of capabilities of electric discharge machining process. When suitable powder is mixed with the dielectric fluid than it increases the conductivity of dielectric fluid, which further decreases the insulating strength of the dielectric fluid in order to increase the spark gap distance between the electrode and workpiece. This enlarged spark gap flushes out debris uniform. This spark gap makes machaining process more stable, thereby improving material removal rate and surface finish.

When a suitable voltage is applied, the spark gap filled up with additive particles and the gap distance setup between tool and the workpiece increased from 25–50 to 50–150 mm. The powder particles get energized, get accelerated under electric field and start moving in a zigzag fashion. These charged powder particles acts as conductors. The powder particles arrange themselves under the sparking area and gather in clusters. The chain formation helps in bridging the gap between both the electrodes, which causes the early explosion. More rapid sparking within discharge takes place causes faster erosion from the work piece surface thus higher material removal rate.

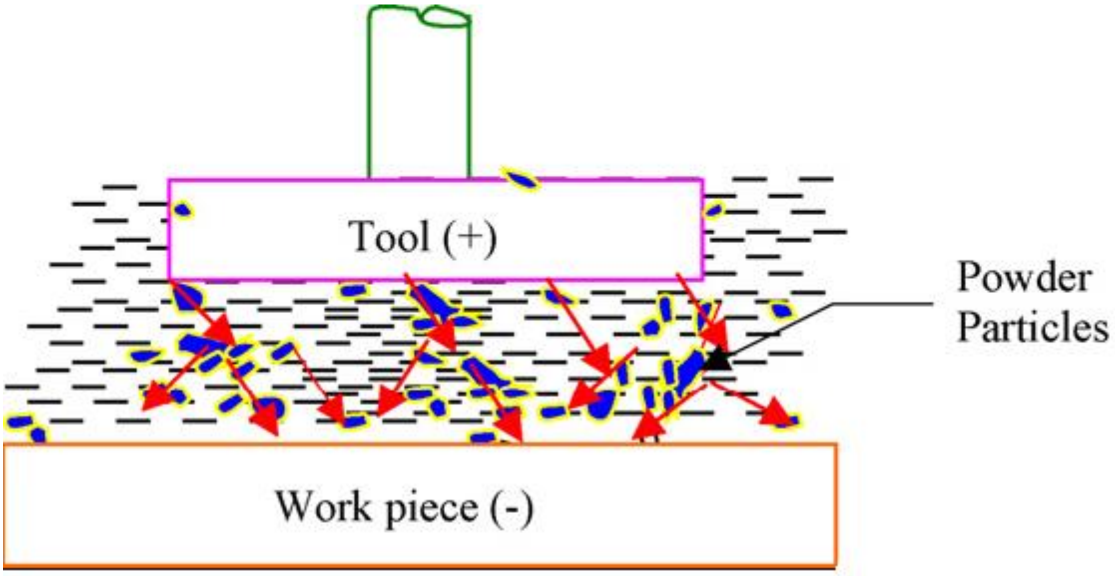


Fig 1.1: Principle of PMEDM [16].

- **Dry EDM:**-In this process a gaseous dielectric used. A thin walled pipe is used as tool electrode through which high-pressure gas or air is supplied. When gas strikes the workpiece, then it removes the debris from the gap and also gives cooling action to the inter electrode gap. The technique reduces the pollution caused due to usage of liquid dielectric; as such dielectrics are environmental friendly, cause no harm to human health and prevent fire hazards. The material removal rate of dry EDM is about 6 times more than that of oil-based EDM. The material removal rate is increased due to the enlarged volume of discharged crater and more frequent occurrence of discharge.[35]

1.4.3 Principle of EDM:-

EDM is a non-traditional machining process based on removing unwanted material in the form of debris from the workpiece with the help of a series of recurring sparks. These sparks are generated by electric pulse generators in micro seconds between electrode and workpiece. The generator is used to apply voltage pulses. A constant voltage is not applied. Only sparking is desired rather than arcing. Arcing leads to localised material removal at a particular point whereas in sparking sparks get distributed all over the tool surface leading to uniform material removal under the tool surface

Both electrode and workpiece is dipped in a dielectric fluid. In this process, there is no direct contact between the electrode and the workpiece thus eliminating mechanical stresses [18].

Its working principle is based on the electro-thermal energy, where electrical energy is used to generate electrical spark and thermal energy of spark is used for material removal. EDM process uses electrical energy which further generates a channel of plasma between the cathode and anode, and turns it into thermal energy.

The workpiece and the electrode are separated by a particular small gap known as spark gap. Pulsed spark occur in this gap filled with an insulating medium [19]. The insulating effect of the dielectric medium helps in avoiding electrolysis effects on the electrodes during machining process. The electrode moves toward the workpiece until the gap is small enough so that the applied voltage is high enough to ionize the dielectric fluid [23].

Different types of dielectric are used as insulating medium such as kerosene, deionised water, edm oil etc. When some potential difference is applied then gap between the tool and workpiece, an electric field would be established automatically by servo-mechanism. Normally tool is connected to the negative terminal of the generator and the workpiece is connected to positive terminal. As the electric field is established between the tool and the workpiece, the free electrons on the tool are subjected to electrostatic forces. The electrons with less work function or bonding energy would be emitted from the tool. Such emission of electrons is known as cold emission. These cold emitted electrons are then accelerated towards the workpiece through the dielectric medium. As they gain energy and velocity, and start colliding with neutral atoms of the dielectric, which generates positive ions and further electrons, which in turn are accelerated respectively toward the cathode and anode. Such collision may leads to ionization of the dielectric molecule which depend on the work function or ionization energy of the dielectric molecule and the energy of the electron. This cyclic process would increase the concentration of electrons and ions in the dielectric medium present in the spark gap. This concentration would be so high that the matter existing in that channel is known as plasma. Channel of plasma has a radius of 10 μm. The electrical resistance of such plasma channel is very low.

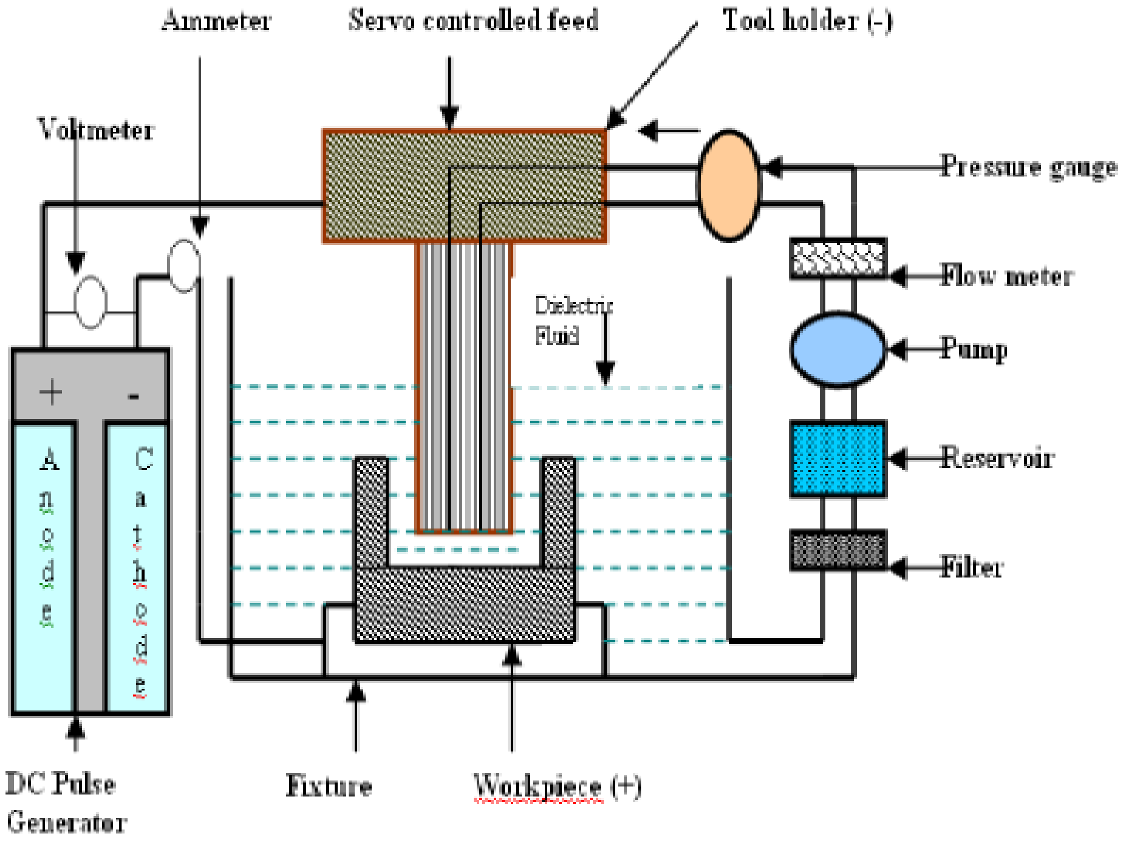


Fig 1.2: Schematic of EDM Process[16].

Therefore a large number of electrons will flow from tool to workpiece and ions from workpiece to tool. This flow of electrons is known as avalanche motion of electrons. Such flow of electrons and ions can be visually seen in form of spark. The ignition of the discharge or spark is initiated by a high voltage, by overcoming the dielectric breakdown strength. Thus the electrical energy is dissipated as the thermal energy of the spark.

When high speed electrons are impinged on workpiece and ions on the tool, then they release their kinetic energy in the form of thermal energy or heat flux. Such intense localized heat flux leads to instantaneous rise in temperature. The temperature generated in this process is in the range of 8000–12,000ºC and heat fluxes up to 1017 W/m^2 are attained. Metal removal takes place due to generation of extremely high temperatures generated by the high-intensity sparks that melt and evaporate the workpiece. The molten metal is removed partially not completely. As the potential difference is withdrawn or when the pulsating direct current power supply occurring between 20,000 and 30,000 Hz is turned off, the plasma channel breaks down. As the plasma channel collapse, there would be sudden reduction in the temperature allowing the circulating dielectric fluid to flush the molten material, it generates pressure or shock waves, which removes the molten material from generated crater on workpiece surface in the form of microscopic debris. Similarly, the positive ions impinge on the tool leading to tool wear.

1.4.4 EDM process parameters

1) **Peak Current: -**This is the most important parameter in EDM machaining process. It may be defined as the actual power used during machaining and it is measured in amperes. During each pulse on-time, the current increases until it reaches a fixed level, which is expressed as the peak current. Higher amperage is used in roughing operations and in cavities with large surface areas. Higher currents will improve MRR, but at the cost of surface roughness and tool wear rate.
2) **Discharge voltage:-** It is a potential and measured in volt. It effect the material removal rate. It is related to the electrode gap and breakdown strength of the dielectric fluid. Before current can flow, the open gap voltage increases until it creates an ionization path through the dielectric. Once the current start flowing, then voltage drops and stabilizes at the working gap level. The preset voltage determines the width of the spark gap between the leading edge of the electrode and work piece. Higher voltage settings increase the gap, which further leads to better flushing of the system and helps to stabilize the cut. Higher open circuit voltage settings increase the gap, which makes flushing conditions better and helps to stabilize the cut. MRR, tool wear rate (TWR) and surface roughness

increases, by increasing open circuit voltage. It is due to increased electric field strength. But the open circuit voltage has a marginal effect on surface hardness.

3) **Pulse On time (T_{on}): -** It is the time period during which actual cutting takes place. It is expressed in micro seconds i.e. μs. Pulse on time is also known as pulse duration and the sparks are generated at certain frequency. During this time period current is allowed to flow through the electrode and work material within a short gap known as spark gap. Material removal is directly proportional to the amount of energy applied during this on-time. This means that energy is controlled by peak current and the span of pulse on-time. Material removal rate and tool wear rate increases with increase in pulse duration. Erosion takes place in the form of melting and then vaporization of both the tool and workpiece takes place during this time period, so with longer pulse duration more material will melt and vaporize. Therefore crater formed will be deeper and broader than shorter pulse on time. But optimum pulse on-time gives higher material removal rate rather than blindly increasing pulse on-time [16].

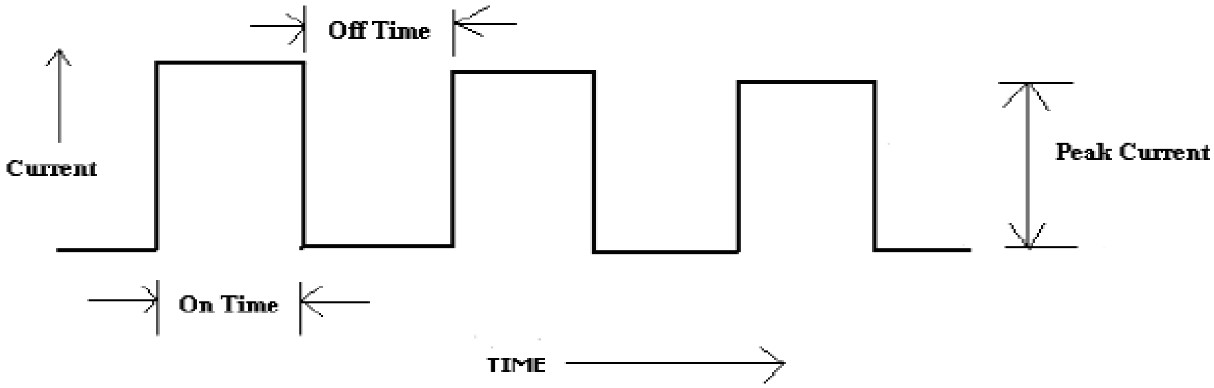


Fig 1.3: Pulse wave form of pulse generator

4) **Pulse Off time (T_{off}):-** It is the time period during which no machining takes place. It is also known as pause time or idle time period. It is the duration of time between the two sparks. So it is considered to waiting interval time period during two pulses. This time allows the molten material to solidify and to be wash out of the arc gap. It is the duration of time in which no machining takes place. It affects the speed and the stability of the cut. There must be sufficient off-time before the next cycle start. Shorter will be the off-time, the faster will be cutting operation. But, if the off-time is too short, the ejected work piece material will not be removed away by the flushing action of the dielectric. Moreover dielctric fluid will not be deionized. This will make next spark unstable. Unstable conditions

cause erratic cycling and retraction of the advancing servo. Off-time must be greater than the deionization time in order to avoid continued sparking at one point.

5) **Duty cycle**:-It is defined as a percentage of pulse on-time to the total cycle time. It denotes the efficiency of the EDM operation. Material removal rate increases with increase in duty factor, because the intensity of spark increases. With the increase in duty cycle, a black layer is produced on the surface of work material and with further more increase of it; the machining becomes unstable duty cycle**.**

$$\textbf{Duty cycle} = \frac{\mathbf{Ton}}{\mathbf{Ton+Toff}} \qquad \text{………...……………Eq. (1.1)}$$

6) **Electrode gap:**-It is the distance between electrode and workpiece during the EDM process. It is also known as spark gap. The tool servo-mechanism is used to control working gap of the set value. Mostly electro-mechanical and hydraulic systems are used to adjust average gap voltage. For getting good performance and high gap stability an appropriate gap should be maintained, the reaction speed must be high and backlash must be zero.

7) **Polarity: -** The polarity of the electrode or workpiece can be either positive or negative. MRR is more when workpiece are connected to negative terminal (-) than positive polarity (+). Because dissociated carbon elements in the dielectric fluid tend to adhere to the anode, which further leads to formation a recast layer [37]. Polarity can affect processing speed, finish, wear and stability of the EDM operation. When a spark is generated electrons are emitted from the negative polarity collides with neutral molecules between the workpiece and electrode and causes ionization process in EDM [36]. As the negatively charged electrons get attracted toward positively charged workpiece, therefore anode material is worn out predominantly. This causes minimum electrodes wear.

8) **Flushing: -** Flushing is used to remove eroded particles from the gap for efficient cutting and for better surface finish of machined material. Flushing brings fresh dielectric fluid into the gap and cools both the electrode and the work piece. Machining time increases with improper flushing as it causes erratic cutting because eroded particles get attached to the workpiece. Therefore for efficient cutting it is necessary to remove the attached particles from the workpiece. The flushing becomes difficult with deeper cavity. Arcing also becomes common when eroded particles are not removed sufficiently. This arcing causes unwanted

cavities which can destroy the workpiece. Arcing commonly occurs during the finishing operation because of the small gap that is required for finishing.

Types of Flushing:-

There are mainly four types of flushing.

Injection flushing: - It is also known as pressure flushing and it is most common and preferred method for flushing. It can be used in two ways i.e. through the electrode or through the workpiece. The dielectrics used in EDM must have high dielectric strength and quick recovery after breakdown. The fluid properties and correct fluid circulating methodology are very important. The dielectric fluid not only forms a dielectric barrier for the spark between the work piece and the electrode but also cools the eroded particles between the work piece and the electrode. The pressurized fluid flushes out the eroded particles and removes the particle in form of debris from the gap as well as from dielectric medium by passing the fluid through a filter system [16].

Suction flushing: - It is also known as vacuum flushing. It is used to remove eroded particles and minimizes secondary discharge as well as wall tapering. It can be used through electrode or workpiece. It does not sucks clean filtered oil but from the work tank. In this will be efficient if work tank oil is clean. It may be dangerous if gases are not removed sufficiently because it may explode electrode. In this very high vacuum is created which can be uproot the electrode from its mount or workpiece is pulled out from the magnetic chuck. Moreover suction flushing is not visible oil stream.

Combined Pressure and Suction flushing:-It is an advance vergen of flushing which has both characteristics of pressure and suction flushing. They are used for molds with complex shapes. This combination method allows gases and eroded particles in convex shapes to leave the area and permit circulation for proper machining.

Jet flushing: - It is also known as side flushing, as it is done by tubes or flushing nozzles which through the dielectric fluid into the gap. Pulse flushing is generally used along with jet flushing.

1.4.5 Electrode material

Engineering materials have high thermal conductivity and melting point is used as a tool material for EDM process. Copper, graphite, copper-tungsten, silver tungsten, copper graphite and brass are used as electrode in EDM. They all have good wear characteristics, better conductivity and better sparking conditions for machining. Different materials have different specialization. Depending on these specializations, they are used accordingly. Copper with 5% tellurium is used for better machining properties. Tungsten has better wear resistance than copper and brass .Brass gives stable sparking conditions and used for specialized applications such as drilling of small holes where the high electrode wear is satisfactory. Graphite can be used with high currents without much tool wear. There are some other factors that affect the choice of electrode material are material removal rate, wear resistance, surface finish, cost of electrode material and material and characteristics of work material to be machined. All these factors are more important in EDM because the machined cavity is a mirror image of tool electrode and excessive wear will block the accuracy of machining.

Electrode material must have resistance to excessive tool wear when it is bombarded by positive ions. Thus the rise in localized temperature must be less by properly choosing its properties or even when temperature increases, there would be less melting. Moreover, the tool should be easily workable as it can be used to machine intricate shaped geometries [20].

Thus the basic characteristics of electrode materials are [38]:-

1) High electrical conductivity: - As current is our cutting tool so higher electrical conductivity or lower resistivity leads to efficient cutting. Electrons are cold emitted more easily and there is less bulk electrical heating.
2) High thermal conductivity :- For the same heat load, the local temperature rise would be less due to faster heat conducted to the bulk of the tool and thus less tool wear.
3) Higher density:-For the same heat load and same tool wear by weight there would be less volume removal or tool wear and thus less dimensional loss or inaccuracy.
4) High melting point: - EDM is a thermal process so high melting point leads to less tool wear due to less tool material melting for the same heat load.
5) Easy manufacturability.
6) Low cost.

The followings are the different electrode materials which are used commonly in the industry [42]:-

1) Graphite
2) Electrolytic oxygen free copper
3) Tellurium copper – 99% Cu + 0.5% tellurium
4) Brass

1.4.5 Dielectric

For a long period, it was thought that the liquids dielectric was crucial during the EDM process, because it can compress the discharge generated bubble and removes debris out of the spark gap. It also cools the melted debris, workpiece and tool. But now a day's gaseous dielectrics are used as they are more economical and environmentally friendly. So they are drawing more attracts more and more attentions from new researchers. As the EDM technology and its fundamental mechanism have been investigated by many researchers, but there are many aspects of the process, which still need attention for enhancing its potential and performance. The influence of the dielectrics and its effect on the process performance is one such aspect which needs to be thoroughly investigated. The physical and chemical properties of the dielectric have significant influence on the EDM performance. Dielectrics significantly affect the productivity and quality of machining e.g. surface with different types of characteristics can be obtained with different types of dielectrics [4].

The dielectrics play a very important role in the EDM process. The dielectrics may be hydrocarbon oil based and water based. Different types of dielectric are used as insulating medium such as kerosene, deionised water, edm oil etc. The insulating effect of the dielectric medium helps in avoiding electrolysis effects on the electrodes during machining process. As whole process is carried out in absence of oxygen so that the process can be controlled and oxidation can be avoided. Oxidation leads to poor surface conductivity (electrical) of the workpiece thus hindering further machining process. So, dielectric fluid must provide an oxygen free machining environment. The electrode moves toward the workpiece until the gap is small enough so that the applied voltage is high enough to ionize the dielectric fluid [40]. The dielectrics used in EDM must have high dielectric strength and quick recovery after breakdown. But at the same time, it should ionize when free electrons collide with its molecule and during sparking it should be thermally resistant. Tap water cannot be used as it ionizes too early and thus breakdown due to presence of salts as impurities occur. Dielectric medium is generally flushed around the spark zone. The dielectric fluid not only forms a dielectric barrier for the spark between the work piece and the electrode but also cools the eroded particles between the work piece and the electrode. The fluid properties and correct fluid circulating methodology are very important. It is also applied through the tool to achieve efficient removal of molten material [19]. Material removal mainly occurs due to thermal evaporation and melting.

Function of dielectric fluid:-

1) To serve as a spark conductor in the spark gap between the tool and work piece.
2) To act as a coolant to quench the spark and to cool the tool and work piece.
3) To carry away the condensed metal particles and to maintain the gap for continuous and smooth operation [40].

Properties of dielectric fluid:-

1) It must have high dielectric resistance, so that it does not deionize easily, but it must ionize when electrons collides with its molecules.
2) It must have high thermal resistance during sparking.
3) It must be chemically inert.
4) It must have low viscosity.
5) It must not contain toxic vapours.

1.4.5 Recast Layer in EDM

Electrical Discharge Machining process is a very quick and relatively less expensive method for making die casting; die inserts but leaves a large number of very high and detrimental surface stresses. If these stresses are not removed completely and properly then it may accelerate thermal stress cracking. During EDM process metal is removed by a series of electrical spark discharges. The contact area melts and vaporizes then solidifies on the surface of the cavity. During each cycle period crater gets larger and larger, as its increasing surface area sinks away the heat from the spark gap until the vaporization temperature is obtained. The melting process continue but during the off time period when the current is switched off, melting stops immediately and all molten material break away in the form of small spherical bubbles is drawn back by the surface tension and resolidifies back on to the rapidly cooler .This thin layer of resolidified material is called recast layer or white layer. The thickness of white layer is approximately 5-15 microns. The topmost or recast or white layer is a brittle and prone to cracking. This is the material that has melted and rapidly solidified. The white layer is densely infiltrated with carbon and has a different structure from its parent metal. The thickness of the recast layer formed on the work piece and the level of thermal damage suffered by the electrode can be determined by analyzing the growth of the plasma channel during sparking. When powders are mixed with dielectric fluids, it then recast layer formed is relatively lower than that for pure dielectrics. The powder particles remove the melted material of the workpiece from the machining zone and restrict the formation of thicker recast layer [45].

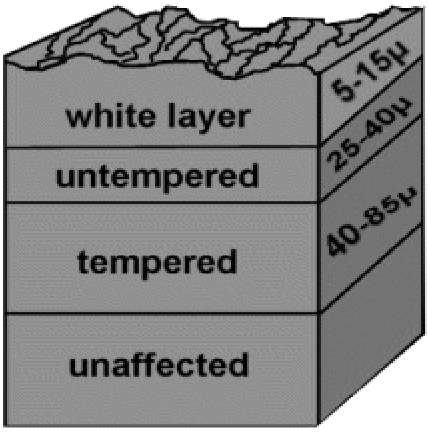


Fig 1.4: EDM layer zones. [Badger Metal Tech, Inc.]

The area immediately below the recast layer is known as heat affected zone (HAZ). This area is partially affected by the high temperature of the spark. The temperature of the material in this area is high, but did not come close to its melting temperature, but reaches a temperature which is high enough to change its temper and reducing its hardness. This layer reaches the austenizing temperature. The thickness of Untempered layer is approximately 25-40 microns and it is also crack prone. The zone may contain re-hardened or hard, brittle untempered martensite formed during the rapid cooling from the austenizing temperature. This can increase crack susceptibility since this microstructure stores considerable energy that decomposes with heat. Depth of zones is dependent on the spark density, volts, and amps of EDM machine. The layer immediately below the untempered layer is known as tempered layer. The thickness of tempered layer is approximately 40-85 microns.

1.4.6 Advantages of EDM Process:-

- Since the tool does not touch the work piece, there are no cutting forces generated therefore very fragile parts can be machined.
- The shape and also the hardness of the materials being used make EDM ideal.
- The EDM process leaves no burrs and the material is flushed away by the dielectric fluid, and by eliminating extra steps it also lowers costs.
- EDM makes it ideal for small, lots of parts, allowing to reduce operating expenses, delivery dates, or reduce inventory The overall production rate compares well with the conventional processes because it can dispense with operations like grinding etc**..**
- The surface produced by EDM consists of a multitude of small craters. This may help in oil retention and better lubrication, especially for components where lubrication is a problem. The random distribution of the craters does not result in an appreciable reduction in fatigue strength of the components machined by EDM.
- The process can be automated easily thereby requiring very little attention from the machine operator.

1.4.7 Limitations of EDM Process:-

- Work piece must be conductive.
- Slower material removal rate.
- Electrical wear may require use of several tools.
- Electrode wear can produce in accuracies.
- Cavities may be slightly tapered.
- Undesirable recast layer may need to be removed.
- Leaves a very shallow, highly stressed surface layer.
- Equipment is expensive.

1.5 Organization of the Study

The thesis work contains five chapters. In Chapter 1 very important basic topics are discussed about the necessity of non-conventional machining, introduction about various non conventional machining processes, working principle of the EDM process and the effect of electrode material and dielectrics on Material Removal Rate, Tool Wear Rate, and Surface Roughness etc. along with organization of thesis. Chapter 2 highlights literature review and recent developments in the EDM and PMEDM. It also contains summery of the literature review, gap found, scope and objective of the study. Design of study which involves the selection of different parameters, their levels, adopting appropriate orthogonal array and introduction to Taguchi method has been deeply and broadly reported in chapter 3. Chapter 4 presents all necessary results and discussions through different graphs and tables, in which all experimental values have been noted. Chapter 5 concludes the results in form of conclusion, flash the limitations of present study and future scope of the work.

CHAPTER 2

LITERATURE REVIEW

This section presents literature review on various fields related to EDM especially on PMEDM and its effects on Material removal Rate and Tool Wear rate along with hardness and roughness of the surface. It also through some light on different kinds of modeling and optimization techniques used in EDM machining process. The literature review shall be used to discuss the effect of different control parameters, different method of modeling and optimization etc. on the quality characteristics in EDM machining.

2.1 Review of EDM machining process:-

Yanzhen Zhang et al. (2013):- conducted experiment by using five dielectrics as the working fluids. These dielectrics were air, oxygen, de-ionized water, kerosene and water-in-oil (W/O) emulsion. In this experiment, the work piece material used was mould Steel 8407 as and Steel needle was used as the electrode. It was reported that the liquid dielectrics are more efficient than gaseous dielectrics in terms of material removal and the cutting efficiency with water-in-oil (W/O) emulsion is much higher than that formed in de-ionized water because in de-ionized water most of the melted material again gets re-solidified in the crater. It is more at shot pulse duration than long pulse duration.

Recast diameter of the crater increases with increase in pulse duration with all types of dielectric fluid. But the real sequence found was water-in-oil emulsion than followed by kerosene oxygen, de-ionized water, air. Water-in-oil emulsion can withstand higher pressure than kerosene and de-ionized water due to its higher viscosity.

The impulsive force acting on the work piece is due to the expansion and contraction of the discharge generates bubble in liquid dielectrics. This impulsive force is more in liquid dielectrics than gaseous dielectrics.

Yan-Cherng Lin et al. (2008):- conducted experiment by using magnetic force with conventional EDM machine in order to make a process of magnetic force-assisted EDM and found that material removal rate can be increased by expelling debris quickly from the machining gap. In this experiment, the work piece material used was mould Steel SKD-61 and Copper was used as the electrode. Dielectric fluid used was kerosene oil.

He varied machining parameters such as peak current and pulse duration to determine the effects on the machining characteristics such as material removal rate (MRR), electrode wear rate (EWR), and surface roughness.

The findings of this experiment are:-

1) The MRR was increased nearly three times with magnetic force-assisted EDM and it remains higher at all energy discharge levels. It increases with increase in peak current and pulse duration.
2) When the machining time was prolonged, then the number of suspending debris in the dielectric was increased, so the debris expulsion was incomplete which further leads to less number of effective sparks. The number of effective sparks can be increased by increasing the debris expulsion by using magnetic force.
3) The EWR was slightly higher but it can be decreased by increasing the pulse-on time. Due to pyrolytic effect of carbon from kerosene dielectric a protective layer is formed on the electrode surface which makes EWR negative.
4) The surface roughness is also finer. The surface roughness increases with increase in peak current.
5) The recast layer is thinner, so crack formation is also less with magnetic force-assisted EDM.

Yan Cherng Lin et al. (2000):- studied the application of ultrasonic machining (USM) with combination of electro-discharge machining (EDM). In this experiment, the work piece material used was Ti-6Al-4V and Electrolytic Copper was used as the electrode. Dielectric fluid used was kerosene oil and distilled water. They conducted experiment by varying machining parameters such as peak current, abrasive size, concentration of abrasive in the dielectric fluid, discharge peak current and pulse duration in order to determine the effects on the machining characteristics such as material removal rate (MRR), electrode wear rate (EWR), relative electrode wear ratio (REWR), surface roughness and thickness of the recast layer. It was found that EDM/USM process can be used to improve the machining efficiency.

The findings of this experiment are:-

1) The MRR of the combination EDM/USM process is higher than the conventional EDM. Distilled water gives higher MRR than kerosene oil. It also increases with the addition of powder. MRR was higher when the 90 g/l of SiC was added, in both kerosene and distilled water. It also increases with increase in peak current as

higher discharged energy increases the vaporization and melting of metal in the machining zone by creating a larger impulsive force of discharge. The abrasive grains of fine size in the dielectric fluid provide a higher MRR.

2) When distilled water is used then REWR is smaller than by using kerosene oil.
3) The EWR increases with the increase in peak current, it decreases as the pulse-on time is increased as carbon element have enough time to stick on the electrode surface. It is due to generation of enormous number of pyrolytic carbon from kerosene oil which forms a protective layer. Therefore, varying pulse duration does not have a clear effect on the EWR.
4) Better surface finish can be obtained with kerosene oil than distilled water because the thermal conductivity of titanium is poor and the cooling rate of distilled water is better than kerosene. The surface roughness increases with increase in peak current.
5) Distilled water provides higher machining efficiency and precision. Since the distilled water has better cooling ability than kerosene oil so the thickness of the recast layer will be less by using distilled water. Because lesser energy will be conducted on machining zone.

G. Kibria et al. (2009):- studied the effect of different types of dielectrics in order to find out its effects on the machining outputs such as material removal rate (MRR),tool wear rate (TWR), overcut, diameteral variance at entry and exit hole and surface integrity. In this experiment, the work piece material used was Ti-6Al-4V and Tungsten was used as the electrode. Dielectric fluid used was kerosene oil. deionized water. B_4C was used as additive powder and mixed with both kerosene oil and deionized water.

The findings of this experiment are:-

1) Material removal rate obtained with deionized water is higher than pure kerosene oil because with deionized water oxide i.e. TiO_2 is formed on surface of work piece but when kerosene oil is used then carbide i.e. TiC is formed on surface of work piece. As TiO_2 melts with lower discharge energy as compared to TiC. MRR also increases when B_4C is mixed with either dielectric used. But when B_4C is mixed with kerosene then MRR is lower than when B_4C is mixed with deionized water. It is due to the efficient distribution of discharge which increases machining efficiency. MRR increases at higher pulse duration.

2) The EWR increases with the increase in peak current, it decreases as the pulse-on time is increased as carbon element have enough time to stick on the electrode surface. It is due to generation of enormous number of pyrolytic carbon from kerosene oil which forms a protective layer. But when deionized water is used, no sticking action takes place. So, tool wear rate is more with deionized water than kerosene oil. When B_4C-mixed deionized water is used then EWR is more than pure kerosene.
3) When deionized water is used then overcut of the microhole is less than when kerosene oil is used at lower discharge energy. But at higher discharge energy overcut will be larger. At lower peak current and pulse-on-time the accuracy of the microhole will be more with deionized water but at higher peak current and pulse-on-time same with kerosene. By using B_4C, both dielectrics show overcut.
4) When deionized water is used, then DVEE of micro holes is less than when kerosene is used. B_4C -mixed dielectrics show an increase in DVEE at low value of discharge current, but B_4C -mixed deionized water shows lower DVEE at higher discharge energy than pure deionized water.
5) When deionized water is used then thickness of white layer or recast layer formed is less than in pure kerosene. White layer thickness increases with increase in pulse duration for both the dielectrics. B_4C-mixed dielectrics show lesser white layer.
6) The surface finish is smooth when pure or B_4C-mixed deionized water is used than when pure or B_4C-mixed kerosene is used.
7) Pure deionized water shows better machining efficiency than kerosene as well as B_4C- mixed dielectrics.

Shailendra Kumar Singh et al. (2013):- optimized the EDM parameters like Pulse-on time, Pulse- off time and peak current to get the better surface finish. In this experiment, the work piece material used was Ti-6Al-4V and Copper was used as the electrode. Dielectric fluid used was kerosene oil. They used L9 orthogonal array based on Taguchi method to conduct a series of experiments to optimize the parameters. It is found that peak current and Pulse off time affects the surface roughness. Pulse on time had the least influence on Roughness.

Han-Ming Chow et al. (1998):- conducted experiment by using two types of powders such as SiC and Al powder in kerosene oil for investigating their effects on the machining output such as material removal rate (MRR),tool wear rate (TWR), surface roughness and the slit expansion. In this experiment, the work piece material used was Ti-6Al-4V and Copper was used as the electrode. Dielectric fluid used was kerosene oil.
The findings of this experiment are:-

1) Material removal rate and surface roughness increases by adding Al or SiC powder in kerosene oil. SiC gives better material removal rate than Al.
2) EWR decreases with addition of SiC.
3) Kerosene mixed with either Al or SiC powder extends the gap between the electrode and the work piece. Superior surface roughness can be obtained by dispersing discharge energy. Al powder with kerosene gives better surface finish as largest gap can be generated with Al powder added to the kerosene owing to its optimal conductivity and suspension.

H.K. Kansal et al. (2007):- used Si powder in kerosene oil in order to determine the material removal rate (MRR). Parameters such as peak current, pulse-on time, pulse-off time, and concentration of powder, gain, and nozzle flushing are used for study. In this experiment, the work piece material used was AISI D2 die steel and Copper was used as the electrode. Dielectric fluid used was kerosene oil. Material removal rate is optimized by using the Taguchi method and ANOVA analysis. It was found that MRR increases with increase in peak current and powder concentration. MRR is affected by peak current, powder concentration, pulse-on time, pulse-off time, and gain. The nozzle flushing has no significant affect on material removal rate.

Uma Batra et al. (2012):- reported the effects of Tungsten powder on micro-hardness of the machined surface. The experiment was conducted by considering peak current, pulse on-time and pulse-off time as variable factors. Process parameters are optimized by using the Taguchi method and ANOVA analysis. In this experiment, three different types of die steels were used as work piece material i.e. OHNS die steel; D2 die steel and H13 die steel and Copper was used as the electrode. Dielectric fluid used was kerosene oil. It is found that due to transfer of tungsten and carbon to the workpiece surface micro-hardness is improved by more than 100% for all the three die steels. The surface of workpiece gets modified because powder particles are inculcated on the surface of workpiece in order to form carbides. Peak current is most important parameter for surface modification.

Khalid Hussain Syed et al. (2013):- developed a empirical model for optimizing the thickness of white layer by using the response surface methodology (RSM). Face centered central composite design procedure is used to plan the experiments. In this experiment, the work piece material used was W300 die steel and Copper was used as the electrode. Dielectric fluid used was distilled water. Al powder was mixed with distilled water. Three process parameters such as peak current, pulse on-time and concentration of aluminium powder are considered for studying white layer thickness (WLT). It was reported that white layer thickness (WLT) increases with increase in peak current as well as with pulse on-time. By increasing the concentration of the aluminum powder, the WLT contains more cracks and voids on the machined surface, but tends to decrease for any value of peak current. The thickness of white-layer will be high with less cracks on the machined surface while using pure distilled water. They found that lower peak current of 6 A, high concentration of Al powder of 4 g/l mixed with distilled water produces minimum thickness of white-layer 17.14 μm with positive polarity.

M. Ali Okka et al. (2010):- conducted a set of EDM fast hole drilling operations in order to explore the effect of single and multi-channel tubular electrodes on material removal rate, electrode wear and micro hardness. In this experiment, two different types of work piece material were used i.e. Inconel 718 and Ti-6Al-4V and two types of electrode were used i.e. Copper and Brass. Dielectric fluid used was deionized water.

The following conclusions can be drawn from the experiments:-

1) It was found that the single-channel electrode gives better material removal rates and lower electrode wear rate. Higher MRR can be achieved by using brass.
2) Micro structural changes due to annealing effect on Inconel 718 and tempering effect on Ti–6Al–4V. Lower hardness is obtained by using multi-channel electrode.
3) The electrode wear ratio is lesser for Ti–6Al–4V. A copper electrode shows lower wear than brass. Multi-channel electrodes generate better surfaces finish than single channel electrodes because of the flushing effect of the multi-channel electrodes which properly removes debris from workpiece and prevents the resolidification of melted metal.

Lei Li et al. (2012):- studied the effect of a bundled electrode on machining output. Different input parameters such as peak current, fluid flow rate, pulse on-time and pulse-off time were selected to investigate their effects on material removal rate (MRR), tool wear rate (TWR). In this experiment, Ti-6Al-4V was used as work piece material and Copper was used as the electrode. Dielectric fluid used was kerosene oil.

It was found that bundled electrodes can endure higher peak current, so MRR will be higher with lower TWR. TWR is less because eroded workpiece particles protect ion reaction on electrode surface which further leads to uniform tool wear. It is greatly influenced by peak current and flow rate. But MRR mainly depends on peak current, flow rate and interactions between peak current and pulse duration. A bundled electrode with multi-hole inner flushing provides superb flushing. Peak current and the fluid flow rate can alter EWR.

Ulas Caydas et al. (2007):- have carried out a study to optimize the process parameters by applying different types of electrode materials. Different process parameters such as pulse current and pulse-on time were choosen to explore the influence input factors on material removal rate, surface roughness and electrode wear rate. In this experiment, the work piece material used was Ti-6Al-4V and Graphite, electrolytic Copper and Aluminium were the three types of electrode used. Dielectric fluid used was kerosene oil.

The findings of this experiment are:-

1) The surface finish of Ti-6Al-4V is poor due to formation of recast layer on the surface, surface micro-cracks, debris. The microstructure of white layer may be hexagonal martensitic. The hardness of white layer is higher than the parent material due to formation of $Ti_{24}C_{15}$ carbides.
2) The average white layer thickness is increasing with EDM parameters. The material removal rate, surface roughness, electrode wear and average white layer thickness increases with increase in current density and pulse duration. Surface crack density depends on average thickness of white layer. Surface cracking can be eliminated for Aluminium and Graphite electrodes whereas copper always produces surface cracks.
3) The material removal rate, surface roughness and electrode wear were increased with each process parameters for all types of electrode material apart from the prolonged pulse duration of 200 μs due non uniform distribution of spark energy.

4) Graphite electrode gives the highest material removal rate, followed by electrolytic Copper and Aluminum. Graphite shows the lowest electrode wear rate due to its higher melting point. Aluminum displays the best surface finish.

Khalid Hussain Syed et al. (2012):- tries to optimize the process parameters so that maximum MRR, low EWR, higher surface finish and minimum white layer thickness can be achieved. They varied various process parameters like peak current, pulse on-time, concentration of the powder, and polarity in order to analyse the process performance. Taguchi method, Signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) are used to optimize the process parameters. In this experiment, the work piece material used was W300 die-steel and Copper was used as the electrode. Dielectric fluid used was distilled water. Aluminium powder was added to dielectric fluid. It was found that distilled water can be used as dielectric fluid and its performance can be improved by the adding Auminium powder.

The findings of this experiment are:-

1) Higher MRR can be achieved by means of positive polarity while better surface finish and lower white layer thickness is achieved by negative polarity. So positive polarity can be opted for rough machining to achieve higher MRR and negative polarity for finishing operation.
2) MRR increases with increase in peak current and with low concentration of powder in positive polarity.
3) EWR decreases with positive polarity and with lower peak current, higher pulse-on time and low concentration of powder.
4) The minimum thickness of white layer is obtained with lower peak current, lower pulse-on time and low concentration of powder in negative polarity.

K. K. Singh et al. (2010):- conducted experiment by mixing chromium powder to dielectric fluid. The process parameters like peak current, concentration of the powder duty cycle, angle of electrode and concentration of chromium were selected to analyze its affect on output variables such as material removal rate, tool wear ratio. In this experiment, the work piece material used was EN-8 steel and Copper was used as electrode. Kerosene oil was used as dielectric fluid. Chromium powder was added with Kerosene oil.

It was observed that TWR decreases with increase in tool angle. The MRR increases with increase in current, tool angle, duty cycle, and powder concentration. After certain level, the MRR tends to decrease due to inefficient flushing. Powder concentration was reported as dominant factor which effects MRR significantly.

K. K. Singh et al. (2011):- investigated the effect of chromium powder on material removal rate, electrode wear rate, surface roughness and white layer thickness. Five process parameters chosen were peak current, pulse on-time, concentration of the powder and diameter of electrode. Taguchi method, Signal-to-noise ratio and ANOVA were used to optimize the process input parameters and to achieve maximum output. In this experiment, the work piece material used was EN-8 steel and Copper was used as electrode. Kerosene oil is used as dielectric fluid. Chromium powder was mixed with Kerosene oil.

It was found that current, powder concentration and electrode diameter are significant input variables affecting both MRR and TWR. MRR increases with increase in powder concentration but up to certain limit otherwise there would be decrease in MRR. TWR increases with lower concentration of powder but then decrease. The role of duty cycle is insignificant on MRR for selected parameters.

Umashankar Rawat et al. (2014):-conducted experiment in order to study the influence of operating factors of tungsten carbide on the material removal rate and tool wear rate. Seven factors at three levels are considered for the study. These factors are peak current, Duty factor, pulse-on time, type of work piece material, type of powder, powder concentration and flushing pressure. The experiments are designed according to Taguchi methodology.

In this experiment, three type of work piece material of Tungsten Carbide were used i.e. W20, W30, W40 and Cylindrical copper tungsten was used as electrode. The dielectric fluid was also mixed with three types of powders i.e. aluminium, graphite and silicon carbide.

It is concluded that peak current and powder affects the material removal rate and tool wear rate. Current, Pulse-on time, type of work piece material, type of powder and Flushing Pressure considerably affect MRR. But duty factor shows least effect.

G Kumanan et al. (2013):- summarizes the material removal rate and surface roughness of Ti-6Al-4V alloy through EDM Process. Four input control factors have been undertaken to know the effects of peak current, pulse-on time, electrode rotational speed and flushing pressure on material removal rate and surface finish. Response surface methodology is used to optimize the parameters. In this experiment, the work piece material used was Ti-6Al-4V and electrolytic Copper was used as electrode. Dielectric fluid used was kerosene oil.

It was concluded that peak current, pulse-on time, electrode rotational speed and flushing pressure all are affecting the output responses. It reveals that surface roughness increases with increase in pulse-on time and peak current because high current and longer pulse-on time produces large machining area and poor surface finish. By using high flushing pressure the surface roughness decreases for all levels of current and then starts decreasing. When the peripheral speed of the electrode increases, the ignition time delay also increases which lowers down the energy transferred for material removal. This gives a better surface finish.

Pankaj Kumar Shrivastava et al. (2013):- developed artificial neural network model to predict the TWR with negligible prediction error. In this experiment, the work piece material used was copper-iron-graphite MMC and Steel rod was used as electrode. Graphite was used as additives powder. Dielectric fluid used was SEO 450. Magnetic forces were used to remove the debris from the dielectric fluid. Input parameters like peak current, pulse-on time; pulse-off time and powder concentration are varied to analyze the tool wear rate. It is seen that graphite powder significantly reduces the tool wear rate. The peak current and powder concentration are the most dominating control factor affecting TWR.

Ved Parkash et al. (2013):- performed an experiment to investigate effect of graphite and copper powder on tool wear rate. They used Taguchi method and ANNOVA to analyze the effect of PMEDM. In this experiment, the work piece material used was EN-31 die steel and Copper was used as electrode. Two powders namely Graphite and Copper were used as additives. Dielectric fluid used was Kerosene oil. A number of control parameters like peak current, pulse-on time, pulse-off time and different types of dielectric were chosen to optimize tool wear rate. It has been concluded that TWR is higher with Copper as compared to Graphite. When peak current and pulse on-time is increased then tool wear rate also increases. This means tool life increases with the use of graphite powder in the dielectric fluid.

Chitra Sharma et al. (2010):- tries to reveal the potential of graphite powder in increasing machining capabilities. A number of control parameters like peak current, pulse on time, duty cycle, gap voltage, retract distance and concentration of graphite powder was choosen to optimize material removal rate. For optimization Taguchi and ANOVA tools are used. In this experiment, the work piece material used was Inconel 718 and Copper was used as electrode. Graphite was used as additive powder. It was found that machining rate increases with addition of graphite powder, concentration of graphite powder in dielectric fluid and peak current.

Murahari Kolli et al. (2014):- evaluates the influence of Span 20 surfactant and Graphite powder mixed in the dielectric fluid on the machining responses of Ti-6Al-4V alloy. Input factors such as discharge current and dielectric with and without powder are used to study the machining responses i.e. material removal rate, surface roughness and tool wear rate. In this experiment, the work piece material used was Ti-6Al-4V and electrolytic Copper was used as electrode. Dielectric fluid used was EDM oil. Graphite was used as additive powder.

It was found that MRR increases, TWR decreases and better surface finish are obtained by the addition of Graphite powder. Due to certain properties such as electrical resistivity, thermal conductivity, particle size, particle density and concentration of powder and surfactant increases MRR and decreases recast layer thickness and TWR. So the surface density of pits, holes and cracks are produced at very minute scale. Surfactant increases the conductivity of the dielectric fluid by reducing its surface tension. Some amounts of material were transferred from electrode to workpiece. The MRR, TWR and surface roughness increases with increase in discharge current. This a less compared to without additives.

Tadashi Asano et al. (2013):- explored the influence of spark gap in powder-suspended Electrical Discharge Machining. In this experiment, the work piece material used was S50C and electrolytic Copper was used as electrode. Dielectric fluid used was kerosene oil. Graphite and Silicon were two powders used for comparison of machining performance.

It was found that mixed power and spark gap are related with each other for single discharge, Si powder breaks insulation at longer gap distances than in Gr powder. Bubbles were seen from the bridge during Gr powder. It is due to short-circuit current.

During surface finish, the mean gap distance depends on type of powder used. Because it is affected by the powder’s capabilities of insulation break and bubble generation.

Mohammed B Ndalimam et al. (2013):- increased the surface micro-hardness of Ti-6Al-4V alloy by adding urea in different concentrations. Peak current, pulse-on time, duty factor and concentration are input control variables used to see their effect on micro-hardness. Response surface methodology is used to optimize the input control parameters. In this experiment, the work piece material used was Ti-6Al-4V and Copper -Tungsten carbide was used as electrode. Urea is mixed in different concentration with dielectric fluid used.

It is observed that both urea and electrode increases the micro-hardness of material considerably. Micro hardness obtained with Cu-TaC is more than Cu because Ta particle also migrate on workpiece material. It also increases with Peak current and concentration of urea in dielectric fluid.

Meena Laad et al. (2014):- investigated the enhancement in surface properties of Ti-6Al-4V alloy machined by EDM process by using graphite electrode. Gap current, pulse on time, and pulse off time were taken as EDM process parameter and micro-hardness was taken as the response output. Most of runs of experiments show 100 % increase in micro hardness. It was observed that gap current, pulse-on time and pulse-off time plays helps in increasing the surface hardness but gap current, pulse-on time are most dominating factor followed by pulse-off time. Because migrated carbon from electrode and dielectric sticks to the surface of workpiece to form titanium carbide (TiC). This increase in the micro hardness can be cosidered as the indicator of surface alloy. ANNOVA and S/N ratios are used for optimization purpose. In this experiment, the work piece material used was Ti-6Al-4V and graphite was used as electrode. EDM oil is used as dielectric fluid.

T.P. Singh et al. (2014):- investigated the migration of tungsten powder to the material surface by suspending tungsten powder in the dielectric fluid. Three input control variables like gap current, pulse-on time and pulse-off time were considered to investigate micro-hardness of the machined surface. Peak current is the strongest factor influencing surface modification.

In this experiment, the work piece material used was OHNS die steel and electrolytic copper was used as electrode. Commercial grade EDM oil is used as dielectric fluid. Tungsten powder was mixed with EDM oil.

It is found that due to transfer of tungsten and carbon to the workpiece surface, there is an improvement of more than 100% in micro-hardness. Tungsten was observed on all machined surfaces in form of carbides and in form of alloyed cementite. Carbon was also present on all machined surfaces in form of solid solutions in ferrite and cementite phases or their independent hard carbides. Such formations increase the micro hardness. Coefficient of friction is higher for PMEDM due to which workpiece shows noteable rise in the micro hardness than the parent material.

Anand .N. Nikalje et al. (2014):- carried out experimental study to identify the effect of different process parameters on material removal rate, tool wear rate, surface roughness and micro hardness. The input control variables selected for study were peak current, pulse-on time and duty cycle. Experiments were designed by Taguchi technique and ANNOVA was used to optimize the process parameters. In this experiment, the work piece material used was AISI O2 and Copper was used as electrode. Electrol EDM oil is used as dielectric fluid.

It was concluded that material removal rate is influenced by peak current, followed by duty cycle, pulse-on time and the interaction of peak current and duty cycle. MRR increases with increase in peak current and duty cycle but decreases with increase in pulse-on time. Tool wear rate increases with increase in peak current and duty cycle. Peak Current has largest contribution towards TWR. Surface Roughness increases with increase in peak current, pulse-on time and duty cycle. There is significant interaction between the peak current and pulse-on time. Thus good surface finish can be obtained by using low values of peak current and pulse-on time. Micro Hardness depends on pulse-on time and duty cycle and increases with their increase. It is due to high temperature and duration for which distortion on surface is made.

Apiwat Muttamara et al. (2012):- reported the effect of input control process on surface hardness. The micro-hardness values before and after the spark are compared. The experimental input parameters used are peak current, pulse-on time and pulse-off time. In this experiment, the work piece material used was AISI P20 and Copper was used as electrode. Fluid oil Shell 2A is used as dielectric fluid.

It was seen that on hardened workpiece duty factor showed less surface hardness, but on annealed and non-heat treated workpieces showed increased hardness that will increase with the increase in peak current and duty factor. On non-heat treated materials, pulse-on time increases the micro hardness due to higher duty factor, that would further leads to increase in duration of the discharge, thereby creating more heat per cycle before it is cooled instantly by dielectric fluid. The pulse-off time and peak current showed a minute effect on micro hardness because during pulse-off time, there is no spark so no heat gets generated. But it showed a great effect on material removal rate since the less pulse-off time more the pulse-on time would result in higher duty factor.

G.Naveen Kumar et al. (2014):- tries to investigate effect of kerosene mixed with different powder on material removal rate and surface roughness. A number of input control variables such as type of material, peak current, pulse-on time, duty factor, gap voltage and type of powders have been selected to measure the process performance. In this experiment, two work piece material used were AISI D3 Steel and EN-31 steel along with electrolytic copper as electrode. Kerosene is used as dielectric fluid. Copper and aluminium powders were mixed in kerosene oil.

It has been seen that by mixing either powder increases the material removal rate by improving the surface finish because PMEDM easily breakdown the discharge by increasing the discharge gaps which further widens the discharge passage or plasma channel. So it leads to creation of evenly distributed large and shallow cavities on the work piece. With the increase in peak current and pulse-on time, MRR increases. Aluminium powder produces better surface finish than copper powder and dielectric without powder.

G. Bharath Reddy et al. (2014):- studied the effect of micro-sized owders on different types of steels. Six input control factors have been undertaken to know the effects of material type, peak current, pulse-on time, duty factor, gap voltage and fine powders in dielectric fluid on material removal rate and surface finish. Taguchi design is used to design the experiments. In this experiment, the work piece material used was high carbon high chromium steel and graphite was used as electrode. Kerosene is used as dielectric fluid. Copper and aluminium powders were mixed in kerosene oil.

It has been concluded that aluminium powder generates superior surface finish than copper powder and dielectric without powder. Peak current, pulse-on time and type of powder increases material removal rate.

D.M. Nyaanga et al. (2013):- conducted experiments in order to investigate the effect of different powder on machining responses of mild steel. Different control variables like types of powder and concentration of different powder are used to study the output control variables i.e. material removal rate and electrode wear rate. In this experiment, the work piece material used was mild steel and graphite was used as electrode. Distilled water is used as dielectric fluid. Three different types of powder i.e. copper diatomite powder and aluminium was mixed with dielectric fluid. ANNOVA has been used to analyze the result.

It was revealed that MRR increases while EWR decreases by adding diatomite, aluminium and copper. Aluminium powder gives best process performance. Higher MRR is obtained by using diatomite followed by copper and than aluminium powder.

B. Ramu et al. (2014):- reported the effect of peak current and concentration of copper powder on process performance. In this experiment, the work piece material used was high carbon high chromium steel and copper was used as electrode. EDM oil and deionized water is used as dielectric fluid. Copper powder was mixed with both dielectrics. It has been found that material removal rate and surface finish increases with addition of copper powder but upto certain concentration then it starts decreasing.

2.2 Summary of given literature

- Several authors have reported on the improvement in surface finish by using different types of dielectrics like distilled water de-ionized water and kerosene oil and also by using different types of additives. By using kerosene as dielectric surface hardness increases. Surface finish with kerosene is better than distilled water.
- MRR increases with distilled water, deionized water and also when powders like SiC, B_4C, Al, Tungsten powder etc. were added as additive.
- Several authors have reported that MRR increases with addition of powders like copper, aluminium, graphite, SiC, B_4C, chromium etc.

- Graphite and aluminium powder improves MRR along with glossy surface finish, by increasing the conductivity of the dielectric fluid.
- Smaller abrasive grains in the dielectric fluid provide a higher MRR with better surface finish.
- Some papers quoted that there is increase in tool wear rate with increase in peak current, pulse-on time but some comes out with reverse output.
- Several authors have reported on the improvement in EDM parameters by utilizing different types of electrode materials i.e. graphite, electrolytic copper and aluminium.
- Different process input variables such as, peak current, pulse-on time, pulse-off time, duty cycle, flush, different types of electrode materials, different types of powders etc. are used to explore the effect on machaining process performance.
- Material removal rate, electrode wear rate, relative wear rate, surface roughness, recast layer and micro-hardness are choosen as output responses.
- Most of authors have used surface response methodology but only few used Taguchi method, grey relational analysis method and Fuzzy logic etc.
- Micro-Hardness increases with increases with increase in certain machining input parameters. It also increases with addition of powder like graphite and aluminium mostly with hydrocarbon dielectrics but also with distilled water at lower intensity.

2.3 Gaps in the reviewed literature

- In most of papers machining of Ti-6Al-4V, researchers compared machining parameters by using (de-ionized water + B_4C), (distilled water + Sic), (kerosene oil + Al) and (kerosene oil + B_4C).
- Different powders such as graphite, copper, aluminium, Sic, B_4C are used with materials other than Ti-6Al-4V.
- Only Copper bundled electrode is used, other bundled electrode i.e. of Brass, Graphite, Aluminium may be used.
- Very limited literature has been used Taguchi method and ANOVA analysis to achieve optimized machining parameters.
- No one has used the combination of kerosene oil mixed graphite powder and kerosene oil mixed copper powder with Ti-6Al-4V alloy.

2.4 Objective of the Study

1) Different powders such as graphite, copper, aluminum, Sic, B_4C has been used. There are several other powders such as chromium, nickel, vanadium etc. can be used. Both copper and graphite is very high conductive material, so it would be interesting to study the effect of copper mixed dielectric and graphite mixed dielectric on material removal rate, tool wear rate, surface finish and micro-hardness.
2) To compare the results of copper powder with the results of graphite powder.
3) To use Taguchi method and ANOVA analysis for optimizing the input control variables.
4) To find out the best result from the different experiment trials by using multi-response optimization technique i.e. grey relational analysis.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 Introduction

This chapter describes the design of this thesis work. It will highlight the experimental work which is includes the formation of L-27 orthogonal array based on Taguchi design. This design reduces the total number of experiment to 27. This chapter include the research methodology, basic information and concentrations regarding constituents of the proposed material, equipments and instruments required to study the machining characteristics of Titanium alloy (Ti-6Al-4V) by using EDM machine.

3.2 Materials

For the study of Titanium alloy (Ti-6Al-4V), we require Work piece, Electrode, Powder and Dielectric. The specifications are as following:

3.2.1 Work piece

Ti-6Al-4V has been selected as a work piece. It is the most common and widely used titanium alloy and comes in the category of difficult-to-machine materials, so it does not seems viable to machine it with conventional machining or chip removal process. It is due to their susceptibility to work hardening during machining by conventional machining processes. It has good machinability and excellent mechanical properties up to 400º C i.e. excellent resistance to fatigue and crack propagation. It has good electrical conductivity and thermal conductivity. When compared to other metals, titanium has lower thermal conductivity, electrical resistance and thermal expansion, but it has high strength to weight ratio. Ti-6Al-4V has 7 to 10 times higher electrical resistance, 7 to 8 times lower heat conductivity and a 10 % to 15 % higher melting temperature than the AISI 1040 steel which is extensively used in making machine elements and in die applications.

The heat generated during machining does not get easily dissipated because Ti-6Al-4V is a poor conductor of heat. So the cutting edge of tool damaged rapidly, causing very short tool life because of heat transmitted to it. It has a strong affinity to alloy with cutting tool materials at high cutting temperatures, causing palling, welding and smearing on tool surface. High electrical resistivity or low electrical conductivity makes EDM of Ti-based alloys more difficult with respect to Ni-based super alloys. During EDM of Ti-6Al-4V, a low level of current flows through the machining gap due to the high electrical resistance of workpiece material. Ti-6Al-4V is also known as titanium grade 5 or Ti-64. Ti-64 is a metal that contain a mixture of titanium and other chemical elements as shown in table 3.1.

Table 3.1: Chemical composition of Ti-6Al-4V

	Ti %	**Al%**	**V%**	**Fe%**	**C%**	**O%**	**N%**	**H%**
Composition of Ti-6Al-4V	89.464	6.08	4.02	0.22	0.02	0.18	0.01	0.0053

It has a number of benefits, but biggest one is heat treatable. This grade has excellent combination of properties such as strength, corrosion resistance weld and fabricability. Due to its high specific strength, high corrosion resistance and high temperature strength within a temperature range, it can be used in various engineering field application. In a variety of weight reduction applications, where weight reduction is a critical obligation like in aerospace industry, Ti-64 alloys can be used in making a number of components in jet engines, particularly disk and fan blade components of the compressor. On the other hand it cannot resist at high temperatures as HRSA alloys, so it cannot be put in use at operating conditions above 595°C. However due to high cost of raw material and its high processing cost limits their use in military applications, aircraft, spacecrafts, automotive, marine equipment, medical devices, highly stressed components such as connecting rods of expensive sports cars, some premium sports equipment and consumer electronics. They are widely used in making gas turbine engines cooler, pre-ignition areas around the compressor, casings, fan blades, high pressure blades and discs or rotors. It is stronger and 45% lighter than common and low-carbon steels. It is only 60% heavier than aluminium alloys but two times stronger. Titanium does not get corroded with sea water, thus used in making propeller shafts, rigging and other parts of boats that are exposed to sea water.

Biocompatibility of Ti-6AL-4V is superb, especially when direct contact with tissue or bone is required. In certain loading conditions it has poor shear strength and poor surface wear properties. Due to its poor shear strength it becomes undesirable for bone screws or plates. When it comes in sliding contact with itself and other metals, then it tends to seize because of its poor surface wear resistance. The surface wear resistance can be improved by certain surface treatments like nitriding and oxidizing.

According to use it can be classified into three typs i.e. α phase titanium, β phase titanium and (α+β) phase titanium. α phase titanium has good machining properties followed by (α+β) type titanium and β type titanium. α phase titanium and (α+β) type titanium are mostly used in different industries. α phase titanium is the more ductile phase and beta-phase titanium is stronger but less ductile.Ti-6AL-4V titanium alloy belongs to (α+β) type titanium alloy which contains favorable synthesized mechanical property.

Table 3.2 Physical and mechanical properties of Ti-6Al-4V

Physical Property	**Typical Value**
Density (g/cm3)	4.42
Melting range (°C±15°C)	1,649
Specific heat (J/Kg °C)	560
Thermal conductivity (W/m K)	7.2
Electrical resistivity (μΩ cm)	1.7
Tensile strength (MPa)	897
Elastic modulus (GPa)	114
Young's modulus (GPa)	110
Hardness Rockwell C	36
Poisson ratio	0.33

3.2.2 Electrode

Commercial copper with 99% purity having electrical conductivity 5.69 × 10^{-6} S m^{-1} would be used as tool electrode. Copper is a chemical element with symbol Cu and atomic number 29. It is a ductile metal with very high thermal and electrical conductivity. Pure copper is soft, malleable and gives reddish-orange appearance. It is a good conductor of heat and electricity. Moreover Copper electrode shows high cutting ability and less tool wear rate. There are some other factors that affect the choice of electrode material are material removal rate, wear resistance, surface finish, cost of electrode material and characteristics of work material to be machined. Due to these properties it is selected as electrode in this study.

The transistorized and pulse-type power supplies make electrolytic or pure Copper most admirable metallic electrode material because Copper electrode along with certain power supply settings are subjected to low wear burning and also compatible with some polishing circuits of advanced power supplies. Moreover Copper can generate very fine surface finish without using special polishing circuits due to its surface integrity, which provides it high resistance to DC arcing even in poor flushing conditions. Female electrodes on a Wire EDM are made from Copper for successive use in reverse burning punches and cores in EDM.

Copper is used as primary electrode material, because graphite makes tool making culture untidiness.. Copper electrodes are favored material for all high speed small hole applications relating to aerospace alloys as well as Carbide.

Table 3.3: Properties of electrode materials

Physical Property	Typical Value
Density (g/cm^3)	8.905
Melting point (ºC)	1083
Specific heat (J/Kg °C)	385
Thermal conductivity (W/m K)	338
Electrical resistively (μΩcm)	8.9
Thermal expansion co-efficient (μ/°C)	16.7
Hardness (HB)	100

3.2.3 Powders

Two powders are used in this study i.e. Graphite powder and Copper powder. These are suspended in dielectric fluid to increase its conductivity. A suitable material in powder form is mixed into the dielectric fluid than these two increases the conductivity of dielectric fluid, which further decreases the insulating strength of the dielectric fluid in order to increase the spark gap distance between the electrode and workpiece. This enlarged spark gap flushes out debris uniform. This spark gap makes machaining process more stable, thereby improving material removal rate and surface finish.

When a suitable voltage is applied, the spark gap filled up with additive particles and the gap distance setup between tool and the workpiece increased from 25–50 to 50–150 μm [18]. The powder particles get energized, get accelerated under electric field and start moving in a zigzag fashion. These charged powder particles acts as conductors. The powder particles arrange themselves under the sparking area and gather in clusters. The chain formation helps in bridging the gap between both the electrodes, which causes the early explosion. More rapid sparking within discharge takes place causes faster erosion from the work piece surface thus higher material removal rate.

Both powders increases conductivity of dielectric fluid thereby increases the MRR. Besides increasing MRR it also improves the surface finish by enlarging and widening the discharge channel which reduces the electrical density on the machining zone and thus shallow craters and lower surface roughness is produced [19]. Graphite powder mixed EDM also leads to minimum tool wear and also improves the surface hardness by forming carbides. Due to addition of powders recast layer also becomes thin as they uniformly distribute the spark energy and increases the spark gap between electrode and workpiece. Higher spark gap leads to better flushing so more debris would be removed. When additives are added to the dielectric fluid, it is observed that the machined surface is most uniform and equal. The surface density of pits, holes and cracks are somewhat less compared to without additives.

Table 3.4: Properties of powder materials

Physical Property	**Graphite powder**	**Copper powder**
Particle Size (mesh)	325	325
Percentage purity (%)	>99.5	>99.5
Electrical Conductivity (S $m^{-1)}$	7.9×10^{6}	5.8×10^{6}

3.2.4 Dielectric fluid

Kerosene oil is used as dielectric fluid. The choice of dielectric fluid depends on the surface finish required. The dielectric having high viscosity and high flash point has not been used because it produces high surface roughness and higher cost. The dielectric inheriting lower viscosity and higher flash point are very costly. Due to low cost, easy availability and suitable for most of the applications, it is most commonly used.

It was most and first popular dielectric fluid used in EDM process. It is very convenient to use because it has very low viscosity so it gives enomerous flushing action, which further increases MRR, reduces TWR due to pryolysis of carbon, improves surface finish and increases micro hardness of workpiece by forming carbides. But it has disadvantages like low flash point, high volatility, odour and causes skin reactions. It is a combustible hydrocarbon liquid also known as paraffin. It is a thin, clear liquid which is fractionally distilled from crude oil between 150 °C and 275 °C, leading a liquid composed of carbon chains having density of 0.78–0.81 g/cm^3. It is miscible in petroleum solvents but immiscible in water.

Table 3.5: Properties of Dielectric fluid

Physical Property	**Typical Value**
Density (kg/m^3)	730
Dielectric constant	1.8
Electrical Conductivity (S/m)	1.6×10^{-14}
Dynamic viscosity (mPas)	0.94
Flash point (°F)	120
Pour point (°F)	−53

3.3 Flow chart of experiment

In this section, methodology to do the work is explained briefly. For the analysis Design of Experiment will be used.

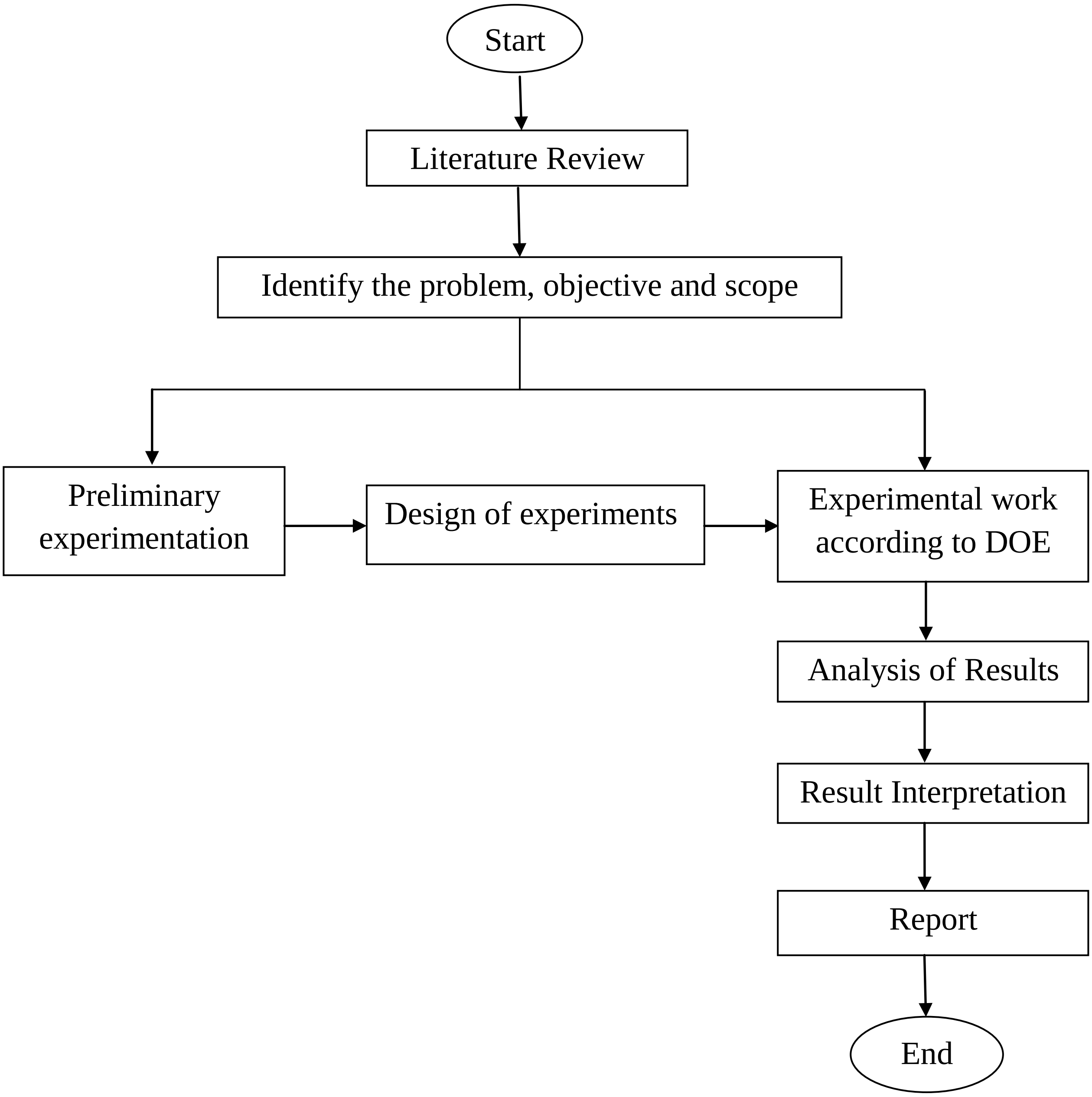


Fig 3.1: Flow chart of experiment

3.4Equipments and Facilities

3.4.1 Electrical discharge machine (EDM)

The experiments will be conducted on EDM machine which are available at Industrial Development Cum Facility Centre, Chandigarh as shown in fig 3.2. Experiments are performed on Elektra EMS-5535 EDM machine. The working tank of this machine has the dimensions of 800mm X 490mm X 325mm.It needs 270 litres of dielectric fluid. The

Fig 3.2: EDM machine

(Photo courtesy: Industrial Development Cum Facility Centre, Chandigarh) machining tank is filled up by Commercial grade kerosene oil. The machine bed can move up to 300 mm in x-axis and 200 mm in y-axis. A big job of approximately 300 Kg can be machined. The worktable can be moved in x-axis and y-axis and tool holder in z-axis. Z –axis movement is controlled by servo-mechanism. Important technical specifications of the machine and list of controls have been tabled in **Appendix A** and **Appendix B** respectively. A spark gap is maintained by servo-mechanism according to the voltage applied. During machining dielectric level indicator maintains the minimum pre-set level above sparking point and turns off the machine if it falls below the minimum pre-set level. A number of input control variables such as pulse-on time, peak current, duty cycle, ignition current etc. can be controlled from the control panel of the machine which is shown in the Fig. 3.3.

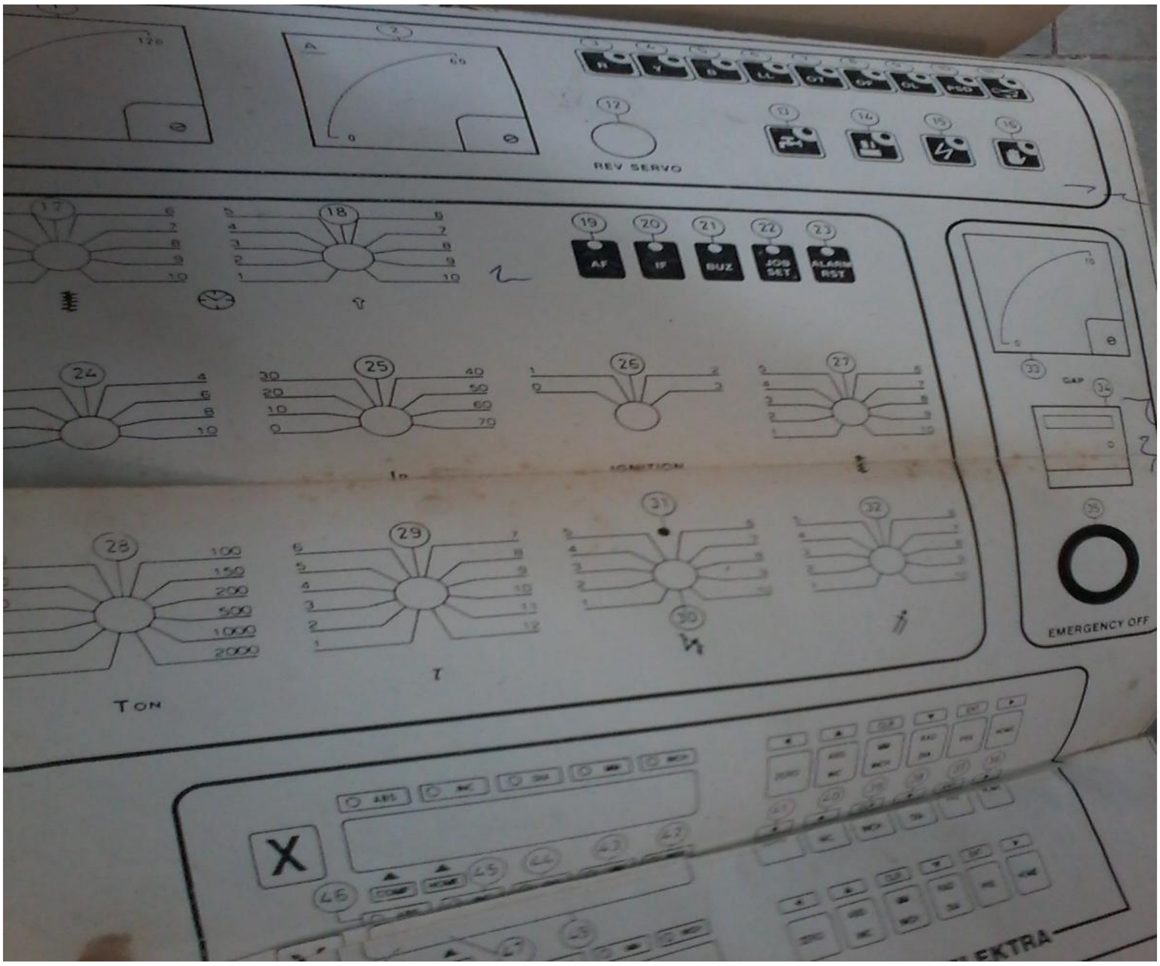


Fig 3.3: Control panel EDM machine

(Photo courtesy: Industrial Development Cum Facility Centre, Chandigarh)

Pulse-on time, pulse-off time and ignition can be set by using respective rotary knobs. Ignition knob has 4-position rotary switch through which the energy of ignition of the discharge channel can be controlled. At position 1, this energy is maximum and decreases as knob is moved progressively. Ignition is kept constant; by keeping knob at position 3 for carrying out tests. Excessive ignition of the discharge channel leads to arcing condition and instability of the machining process. Machining current can be increased slowly and slowly by rotating knob and rotary switch. Both these switches must be kept at minimum position when the sparking starts.

3.4.2 Measuring equipments

- **Micro hardness tester: -** Micro-hardness testing is a technique designed for evaluating the surface hardness of a material on a microscopic scale. In this a diamond indenter is used to make impression on a workpiece by applying a load of 1kg. Vickers hardness is also known as Diamond Pyramid Hardness (DPH) because it takes the shape of the diamond indenter. The impression of diamond indenter is measured microscopically by selecting four corners of the indent and then applied load is used to compute a hardness value. This testing of metals,

Fig 3.4: Micro hardness Tester
(Photo Courtesy: Mechanical Engineering Department, Thapar University, Patiala)

composites and ceramics are done where macro hardness test is not practically feasible. It provides the necessary data when measuring individual microstructures within a larger matrix, or testing very thin foil like materials, or when determining the hardness gradient of a specimen along a cross section. It is available in Mechanical Engineering department, Thapar University, Patiala.

- **Weighing balance:-**The analytical Weighing balance is used to measure the weight difference of Copper electrode before and after the EDM machining of sample used. The CAS Electronics digital weighing balance (CAY 220) is used to weight the samples. The machine has least count of 0.1 mg and maximum capacity of 220 gm. It is available in Chemical Engineering department, Thapar University, Patiala.

Fig 3.5: Weighing balance

(Photo Courtesy: Chemical Engineering Department, Thapar University, Patiala)

- **Optical Emission Spectrometer:-**The chemical composition of work piece material was measured using optical emission Spectrometer Foundry Master (Model DV-6) available at Industrial Development Cum Facility Centre, Chandigarh. Argon gas is used for composition measurement process. The spark formed between the sample and electrode causes the electrons in the sample to emit light which is further used for spectral pattern. By measuring the peaks in this spectrum, it can produce material composition. An accuracy of 0.0001 % is achieved in this equipment.

Fig 3.6: Optical emission spectrometer

(Photo courtesy: Industrial Development Cum Facility Centre, Chandigarh)

- **Surface Roughness Tester:-**Surface roughness will be measured using the Mitutoyo model SJ-400, Germany available at Mechanical Engineering Department, Thapar University, Patiala Mechanical Engineering Department, Thapar University, Patiala. The equipment uses the stylus method of measurement, has profile resolution of 12 nm and measures roughness up to 100 µs.

Fig. 3.7 Surface roughness tester.

(Photo Courtesy: Mechanical Engineering Department, Thapar University,Patiala)

3.5 Design of Experiment (DOE)

It was given by Sir Ronald A. Fisher, the renowned mathematician and geneticist in the 1920. It is a well structured and organized method used to verify the relationship between different factors that are affecting the process and output responses of that process. It involves designing a set of experiments in which all relevant factors are varied systematically so that optimal situation can be figured out. The factor that influences most, those that does not and the existence of their interactions and synergies can also be determined. It is an approach to collect empirical knowledge i.e. knowledge based on the experimental data, not on theoretical models in order to investigate the event to improve performance.

DOE methods require well structured data matrixes. When applied to a well structured matrix, analysis of variance provides accurate results even when matrix relatively small. It requires small set of experiments and thus helps in reducing cost by minimizing optimization costs i.e. to conduct experiments. Different types of design of experiments may be applied in research and development but Taguchi method is the most common and efficient method used for optimization of various parameters.

- **Introduction to Taguchi method**

The Taguchi method was developed by Dr. Genichi Taguchi of Japan. It is a robust design of experiments which leads to reduction in variations so that high quality product can be produced at low cost. This method is best used when number of variables is 3 to 50 and only few interactions takes place and only a few variables contribute significantly. This method provides information that how well the process is functioning, by investigating different parameters that affects the mean and variance of a process performance characteristic. This process formulated a special set of tables called orthogonal arrays. Like in other design such as factorial design which uses all possible combinations, but Taguchi method tests pair of combinations. This needs less data for interpretation, thus saving a lot of time and resources.

- **Orthogonal arrays**

Orthogonal arrays are special set of tables, used to calculate the main effects by using few experimental trails. It is suitable with more than two level factorial experiments where columns for independent variables are orthogonal to one another. The Taguchi arrays can be derived i.e. small arrays can be derived manually; large arrays can be drawn from deterministic algorithms. The arrays can be made by using a number of parameters and the number of levels. Then Analysis of variance (ANOVA) is used to optimize the parameters by plotting the data in tabular and graphical form.

Steps involved in the Taguchi method are as follows:-

1) Define the process objective or a target value for a performance measure of the process. The target value may be minimum or maximum. This may be a flow rate, temperature etc.
2) Decide the design parameters and their level affecting the process. Parameters are variables that affect the performance measure and can be easily controlled.
3) Construct the orthogonal arrays for design parameters by selecting the number of parameters and levels of each parameter.
4) Conduct the experiments as per as orthogonal array in order to collect the data.
5) Determine the effect of different parameters on the performance measures by interpreting the collected data.
6) Optimize the parameters by using analysis of variance (ANOVA) by plotting the data in tabular and graphical form.

3.6 Signal-to-noise ratio for Response Characteristics

In the Taguchi method, S/N ratio is the ratio of signal-to-noise, where signal represents the desirable values i.e. mean of the output characteristic and noise represents the undesirable value i.e. the square deviation of the output characteristic. The parameters that affect the output can be categorized into two categories i.e. controllable factors and uncontrollable factors.

A. **Controllable factors**: - these are those factors which can be easily adjusted and set by the researcher, also known as design factors. These are of three main types:-

1) Target Control Factors (TCF):-These are those factors which affects the average levels of the response of interest. These are also known as signal factors. In my thesis work they are peak current, Pulse-on time, Polarity.
2) Variability Control Factors (VCF):-These are those factors which affects the variability in the response. In my thesis work there is only one VCF factor i.e. Time.
3) Cost factors:-These are those factors which affect neither the mean response nor the variability but adjusted according to economic requirements. e.g. In my thesis work an experimental container has been developed in workshop having the

dimensions of 11 X 8 X 16 inches, which has the capacity of 15 liters. It gives an advantage over using 270 liters of kerosene oil. In order to save more kerosene oil a metallic holding device of 5 X 4.5 X 6 inches is kept in the container. Overall the kerosene oil, time like changing and adjusting, set up, stoppage; researcher's time is being saved.

B. **Uncontrollable factors: -** These are those variation in which researcher has no direct control but changes with operational environment. These are unwanted factors and also known as noise factor.

The Taguchi philosophy is based on the quality loss function. It always endeavour to reduce the variation in a product's functional characteristics. The change in quality characteristic of a product deviating from the desired value is known as signal factor. The effect of the external factors or uncontrollable factors on the result of quality characteristic is known as noise factor. The aim of any experiment is to obtain the best possible S/N ratio.

Three types of S/N ratios are available depending on type of correct objective function it can be used accordingly to the type of response:-

Higher the Better:- _

$(S/N)_{HB} = -10 \log (MSD_{HB})$ ……………….Eq. (3.1)

$MSD_{HB} = \frac{1}{n} \sum_{i=1}^{n} (y_i)^{-2}$

MSD_{HB} = Mean Square Deviation for higher-the-better.

Lower the Better:-

$(S/N)_{LB} = -10 \log (MSD_{LB})$ ………………Eq. (3.2)

$MSD_{LB} = \frac{1}{n} \sum_{i=1}^{n} (y_i)^{2}$

MSD_{LB} = Mean Square Deviation for Lower-the-better.

Nominal the Best:-

$(S/N)_{NB} = -10 \log (MSD_{NB})$ ………………Eq. (3.3)

$MSD_{NB} = \frac{1}{n} \sum_{i=1}^{n} (y_i - y_0)^{2}$

MSD_{NB} = Mean Square Deviation for Nominal-the-better.

Where:-

y_j = Observed value of the response characteristic

y_0 = nominal or target value of the results

n = Number of repetitions

For smaller-the-better type, target value is zero. For larger-the-better, inverse of each large value becomes a small value and again the target value is zero.

For this thesis work, the output responses that have been studied as shown in table 3.6:-

Table 3.6: Output responses

1	Response Name	Material removal rate
	Response type	Higher-the-better
2	Response Name	Tool wear rate
	Response type	Lower-the-better
3	Response Name	Surface Roughness
	Response type	Lower-the-better
4	Response Name	Micro-hardness
	Response type	Higher-the-better

3.7 ANOVA (Analysis Of Variance)

The analysis of variance was developed by Sir Ronald A. Fisher, the renowned mathematician and geneticist in 1920s and 1930s. it is also known as Fisher's ANOVA or Fisher's analysis of variance because Fisher's F-distribution chart is used for testing the statistical significance.

It is a collection of statistical models, their associated procedures, in which the observed variance is partitioned into components due to different explanatory variables. Some useful formulas are:-

DOF = Levels of parameter -1 ……………Eq. (3.4)

Variance $= \frac{SS_i}{DOF}$ …………. Eq. (3.5)

F test = $\frac{\text{Variation due to parameter}}{\text{Variation due to error}}$ ....Eq. (3.6)

e _ pooled = sum of SS due to error and SS of all insignificant factors **……....**Eq. (3.7)

SS' = SS of significant factor - (DOF of that factor × variation due to e _ pooled)

C% = $\frac{SS'}{\text{Total SS}} \times 100$ …………..Eq. (3.8)

If $\mathbf{F_{critical}} > \mathbf{F_{test}}$ only then the factor is significant for the given conditions.

3.8 Selection of parameters

A large number of input control variables can be varied in EDM process; each has its own effect on output responses like Material removal rate (MRR), electrode wear ratio (EWR), surface roughness (Ra), micro hardness of machined surface, dimensional accuracy, white layer thickness (WLT) and overall surface integrity. These input control variables are:-

1) Discharge Voltage
2) Peak Current
3) Pulse-On-Time
4) Pulse-Off-Time
5) Pulse Waveform
6) Pulse Frequency
7) Duty factor
8) Polarity
9) Type of dielectric flushing
10) Type of dielectrics
11) Electrode gap

The effect of the above given parameters on electrical discharge machining process is discussed in detail in the literature review. From the previous research work it was found that out of the above listed parameters, four parameters such as peak current, pulse-on time, pulse-off time and polarity directly affect the MRR, TWR, surface roughness (R_a) and micro hardness of machined surface. Out of these parameters, three parameters have been investigated thoroughly in this research work. In this experimental process only one parameter is varied at a time. Polarity is kept fixed for the whole experiment. Polarity is fixed as straight polarity i.e. electrode negative because at this setting maximum material removal takes place. During this setting of straight polarity, the energy available per discharge at workpiece surface is higher as compared to the electrode.

3.9 Experimental Design

The aim of this thesis work is to investigate the effect of powder on output responses such as material removal rate (MRR), tool wear rate (TWR), Surface finish and micro hardness of the workpiece samples through the material transfer takes place from the powder mixed in the dielectric fluid at various input control variables. So the variables can be figured out as follow:-

1) Two powders have been mixed in the dielectric fluid one by one, i.e. graphite and copper.
2) Three levels of peak current have been used.
3) Three levels of pulse-on time have been used.

For performing the experiments, Taguchi method is used to design the experiments so that an appropriate orthogonal array may be selected by considering above design input variables. The pattern of response of each other cannot be predicated at this stage, so work material is not selected as a variable of orthogonal array. In order to understand the effect of each individual suspended powder on surface modification, the phenomenon of surface modification should be studied so that its behavior can be understood. So the of combination of work material, electrode and powder has been selected for conducting experiments. Three control variables have been selected for designing orthogonal array. The input control variables are peak current, pulse-on time and dielectric.

The four output responses i.e. material removal rate (MRR), tool wear rate (TWR), Surface finish and micro hardness have been selected for this research work. As the quality of the products directly depends on the surface roughness and micro hardness from the point of lubrication retention and life of the product respectively, so the effect of input control variables on output responses will be studied. After conducting the experiments the data will be analyzed as per Taguchi method to find out the optimum machining condition and their percentage contribution.

The input control parameters that have been kept constant during the experimentation are shown in table 3.7.

Table 3.7: Fixed Input control Parameters

S. No.	Parameters	Fixed Value
1	Open circuit voltage (V)	100 ± 5%
2	Powder concentration in dielectric (g/lit)	6
3	Depth of cut (mm)	0.1
4	Type of Dielectric	Kerosene oil
5	Polarity	Straight

3.9.1 Selection of parameters and their levels: -

With the help of literature review three parameters have been selected are peak Current, pulse-On-Time and dielectric as shown in Table 3.8.

Table 3.8: Parameters and their levels

Parameter	Symbol	Unit	Level		
			Level 1	**Level 2**	**Level 3**
Peak Current	A	A	3	6	9
Pulse-On-Time	B	μs	10	20	30
Type of Dielectric	C		Kerosene oil	(Kerosene oil + Cu)	(Kerosene oil + Gr)

3.9.2 Selection of orthogonal array

In this experiment, three parameters at three levels has been selected. The degree of freedom of a three level parameter is 2. So the degree of freedom for this experiment is 8. From the literature review it has been found that there are interactions between current & pulse-on time, pulse-on time & dielectric, current & dielectric. For these interactions the degree of freedom is 12. Therefore the total degree of freedom becomes 18. So degree of freedom of orthogonal array selected should be higher than total degree of freedom of the experiment. Therefore orthogonal array L27 is selected. Parameters and their interactions with their degree of freedom are shown in Table 3.9.

Table 3.9: Parameters and their degree of freedom

Interactions	Units	Degree of freedom
Peak Current(A)	Ampere	2
Pulse-On Time(B)	μs	2
Dielectric(C)	-	2
AXB	-	4
AXC	-	4
BXC	-	4
Total		18

For our problem, L27 has been taken which has an 18 degree of freedom. So there should be18 columns. With the help of Taguchi method and orthogonal array, a table has been drawn for our problem as shown in Table 3.10.

Table 3.10: Standard L27 orthogonal array (Taguchi method)

S.NO.	**Peak Current**	**Pulse-On Time**	**Dielectric**
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	2	1	1
11	2	1	2
12	2	1	3
13	2	2	1
14	2	2	2
15	2	2	3
16	2	3	1
17	2	3	2
18	2	3	3
19	3	1	1
20	3	1	2
21	3	1	3
22	3	2	1
23	3	2	2
24	3	2	3
25	3	3	1
26	3	3	2
27	3	3	3

3.10 Experimental set up for powder mixed in the dielectric

Experiments have been performed on Elektra EMS-5535 EDM machine. The working tank of this machine has the dimensions of 800mm X 490mm X 325mm. It needs 270 litres of dielectric fluid. So large amount of a metal powders would be required for mixing in such a large tank in order to obtain desired concentration of powder in dielectric fluid for process. So, new experimental container has been developed in workshop having the dimensions of 11 X 8 X 16 inches, which has the capacity of 15 liters of dielectric fluid as shown in fig 3.8.

Fig 3.8: Schematic diagram of PMEDM experimental set-up.
(Photo courtesy: Industrial Development Cum Facility Centre, Chandigarh)

This is made up of mild steel sheet of 1.6 mm thick, called the machining container. The height of the machining container is kept above the height of the main working tank so that powder mixed dielectric does not enter into the main tank. A stirrer is also placed on the top of container so that powder can be mixed uniformly. Then it has been placed in the existing tank of EDM machine and experiment has performed in this machining container. The EDM machine tank is filled up by EDM oil and machining container is filled by desired dielectric fluid. In order to save more kerosene oil a metallic holding device of 5 X 4.5 X 6 inches is placed in the container. A small dielectric circulation pump is installed in machining container for proper circulation of powder mixed dielectric fluid into the spark gap between tool and work piece material facing each other. On the completion of the each individual experiment, the powder mixed dielectric is siphoned off into a separate container by using a rubber tube. After changing the work piece position and machine setting, the tank is again filled with powder mixed dielectric fluid for new experiments.

The following points must be kept in mind while performing experiments with powder-mixed dielectric fluid are:-

1) The powder should not enter into the main dielectric tank and the filtering unit in order to avoid the filtering of powder particles.
2) The dielectric fluid must be constantly stirred or circulated so that powder does not get settled down and uniform concentration can be obtained.
3) Proper conductivity must be maintained between the work piece and electrode.
4) Powder must not get wasted, so machining must be done in small parts.

CHAPTER 4

RESULTS & DISCUSSION

This chapter contains the description of the experimental work which has been performed on EDM machine along with the outcome of the experimental work. In this experimental work study has been conducted to investigate the effect of powder on the material removal rate, tool wear rate, surface roughness and micro hardness by using Ti-6Al-4V as the raw material. On the basis of response outcomes, signal to noise ratio has been calculated, graphs have been produced and then results are interpreted. Three sets of experiments have been conducted as under:-

1. Experiments with no powder as additive.
2. Experiments with Copper powder as additive.
3. Experiments with Graphite powder as additive.

4.1 Conduct of experimental work

The experiment has been conducted after proper planning by choosing appropriate workpiece material, electrode, dielectric fluid and powders as shown in table 4.1.

Table 4.1: Three different sets of experiments

Material/Workpiece	Ti-6Al-4V		
Electrode	Copper		
Dielectric fluid	Kerosene oil	Kerosene oil + Cu	Kerosene oil + Gr

Taguchi methods have been used for designing experiment, according to which L27 orthogonal array has been selected. Experiments has been performed according to the set of combinations of factors as per as in L27 orthogonal array. Three input control variables are chosen such as peak current, pulse-on time and dielectric. All these factors have three levels. For current, pulse-on time and dielectric values at various levels are 3, 6 and 9 A; 10, 20 and 30 μs and No, Copper and Graphite are additive respectively. Ti-6Al-4V and Copper is used as workpiece and electrode respectively.

Once all the parameters and their levels have been selected, experiments are performed. Their results are reported in Table 4.2. then results are interpreted analytically as well as graphically. For analysis the results graphs are generated by using MINITAB which shows the effects of all input control variables on output responses. Then ANOVA has been applied for evaluating the contribution of each input control variables in each output response. Material removal rate (MRR), tool wear rate (TWR), surface roughness (R_a) and micro hardness is considered as output responses. Then signal to noise ratio has been calculated for each response i.e. for MRR and hardness, higher the best and for TWR and surface roughness, lower the better approach are used. After this optimal condition has been calculated for material removal rate (MRR), tool wear rate (TWR), surface roughness (R_a) and micro hardness.

The pictures of the specimen after performing the experiments are shown in the Figure 4.1.

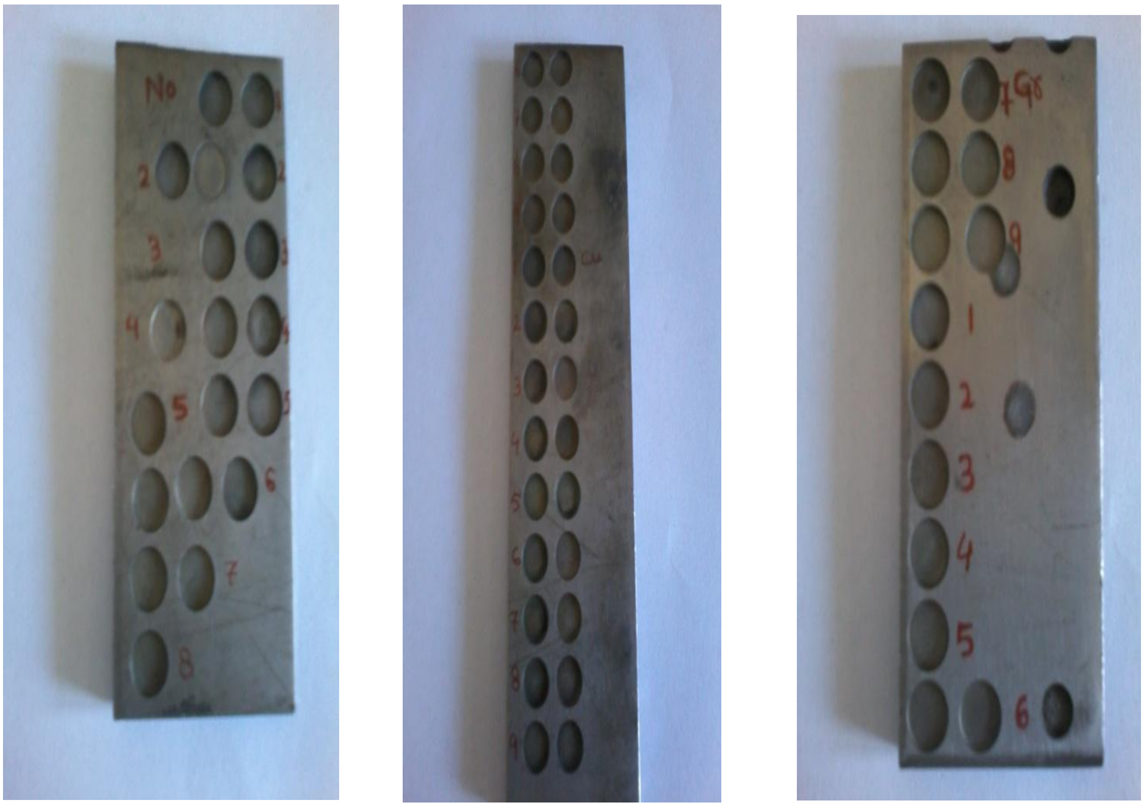


Fig. 4.1: Specimen after EDM machining

Table.4.2: Values of various responses

SNo:	Peak Current	Pulse-On Time	Dielectric	MRR (mm^3/min)	TWR (mg)	Surface Roughness(μm)	Micro Hardness(hv)
1	3	10	No	0.1717	15	2.24	684.273
2	3	10	Cu	0.2648	13	2.02	725.532
3	3	10	Gr	0.3744	10.9	1.73	777.674
4	3	20	No	0.192	7.2	2.68	696.231
5	3	20	Cu	0.3182	6.8	2.17	741.25
6	3	20	Gr	0.4644	6.4	1.97	805.757
7	3	30	No	0.2691	3.6	2.88	733.482
8	3	30	Cu	0.3889	3.4	2.58	788.481
9	3	30	Gr	0.5344	3	2.16	842.116
10	6	10	No	0.2294	14.4	3.04	767.752
11	6	10	Cu	0.3054	11.2	2.76	820.325
12	6	10	Gr	0.471	9	2.59	888.710
13	6	20	No	0.2667	10.9	3.54	812.717
14	6	20	Cu	0.382	8.2	3.17	871.359
15	6	20	Gr	0.5561	7.7	2.94	929.046
16	6	30	No	0.3835	4.8	3.67	852.846
17	6	30	Cu	0.514	4.3	3.35	926.844
18	6	30	Gr	0.6346	4	3.07	945.813
19	9	10	No	0.2648	18.6	3.89	888.710
20	9	10	Cu	0.4008	17.5	3.69	955.262
21	9	10	Gr	0.6441	16.9	3.52	991.923
22	9	20	No	0.3542	17.5	4.13	914.906
23	9	20	Cu	0.552	12.4	4.06	977.220
24	9	20	Gr	0.7281	11.2	3.87	1072.503
25	9	30	No	0.5655	6.1	4.38	944.533
26	9	30	Cu	0.7177	5.4	4.15	1030.628
27	9	30	Gr	0.9819	4.9	3.99	1115.6

4.2 Material Removal Rate

The responses with S/N ratio for material removal rate (MRR) achieved by experiments are tabled in table.4.3 are:-

Table.4.3: Response table for Material Removal Rate

SNo:	Peak Current	Pulse-On Time	Dielectric	MRR(mm^3/min)	S/N Ratio
1	3	10	No	0.1717	-15.30459
2	3	10	Cu	0.2648	-11.54164
3	3	10	Gr	0.3744	-8.53328
4	3	20	No	0.192	-14.33397
5	3	20	Cu	0.3182	-9.94599
6	3	20	Gr	0.4644	-6.66215
7	3	30	No	0.2691	-11.4017
8	3	30	Cu	0.3889	-8.20324
9	3	30	Gr	0.5344	-5.44267
10	6	10	No	0.2294	-12.78813
11	6	10	Cu	0.3054	-10.30261
12	6	10	Gr	0.471	-6.53958
13	6	20	No	0.2667	-11.47953
14	6	20	Cu	0.382	-8.35873
15	6	20	Gr	0.5561	-5.09694
16	6	30	No	0.3835	-8.32469
17	6	30	Cu	0.514	-5.78073
18	6	30	Gr	0.6346	-3.94999
19	9	10	No	0.2648	-11.5416
20	9	10	Cu	0.4008	-7.94144
21	9	10	Gr	0.6441	-3.82093
22	9	20	No	0.3542	-9.01502
23	9	20	Cu	0.552	-5.16121
24	9	20	Gr	0.7281	-2.75617
25	9	30	No	0.5655	-4.95134
26	9	30	Cu	0.7177	-2.88114
27	9	30	Gr	0.9819	-0.15865

Table 4.4: ANOVA table for Material Removal Rate

Source	DOF	SS	Variance	F $_{Calculate}$	F $_{Table}$	SS'	C (%)	
Peak Current (A)	2	0.23210	0.11605	31.53	4.46	0.22690	28.01	S
Pulse On time (B)	2	0.17498	0.08749	23.77	4.46	0.16978	20.95	S
Dielectric (C)	2	0.27127	0.13564	73.71	4.46	0.26607	32.83	S
A XB	4	0.01056	0.00264	0.72	3.84			N S
A X C	4	0.07995	0.020	5.43	3.84	0.06955	8.6	S
B X C	4	0.01204	0.00301	0.82	3.84			N S
Error	8	0.02944	0.00368					
Total	26	0.81034				0.81034	100	
e-pooled	20	0.05204	0.0026			0.07804	9.61	

From the ANOVA table 4.4, it is clear that each factor is significant for material removal rate as F calculated value is greater than F critical values found from table at 95% confidence interval. When peak current is increased from 3A to 9A for dielectric without any powder then material removal rate increases by 54.22%. When graphite powder is used and peak current is increased from 3A to 9A then material removal rate increases by 162.22%. For same peak current i.e. 3A and pulse-on time is increased from 10µs to 30 µs then the material removal rate increases by 56.72%. Pulse duration means the time for which machining takes place, during this period workpiece get eroded by vaporization process. The combination of factors like peak current and dielectric have significant effect on the material removal rate. There are other combination of interactions like peak current and pulse-on time; pulse-on time and dielectric, but they are not found significant. These interaction are of great importance as current is directly proportional to discharge energy and powder uniformly distribute the spark energy which further increases the conductivity of dielectric fluid and improves the discharge force, thereby increasing the MRR. Combination of both peak current and dielectric has greater effect on MRR. Other non significant interactions are pooled in error because they are influencing the material removal rate but not at higher level, so they can be considered as error.

Table 4.5: Average values at factor levels for Material Removal Rate

Level	Peak Current (A)	Pulse-on Time (B)	Dielectric (C)
1	0.3309	0.3474	0.2997
2	0.4159	0.4237	0.4271
3	0.5788	0.5544	0.5988
Delta	0.2479	0.2070	0.2991
Rank	2	3	1

For analyzing the optimal value for material removal rate higher the best approach is used i.e. higher value is taken from each factor column. From Table 4.5, it is found that maximum value of delta is 0.2991 which come with powder mixed dielectric. So dielectric is the most significant factor for material removal rate and the optimal combination for material removal rate is analyzed as $A_3B_3C_3$. So the optimal solution of mean of material removal rate for this study has been calculated.

μ_{opt} = $\bar{m}$+ (m_{A3} - $\bar{m}$) + (m_{B3} - $\bar{m}$) + (m_{C3} - $\bar{m}$)

= 0.4419+ (0.5788-0.4419) + (0.5544-0.4419) + (0.5988-0.4419)

= 0.8482 mm^3/min

Here μ_{opt} = desired mean value

Confidence interval has also been calculated for this experimental work.

$$CI = \sqrt{\frac{F_{\alpha,v1,v2}V_e}{n_{eff}}}$$

Where $F_{\alpha,\ v1,\ v2}$ = F ratio

$\alpha = 0.05$ (risk level)

v_1 = degree of freedom for mean (always 1)

v_2 = Total degree of freedom = 26

$\bar{m}$ = average of all experiment trial

$$n_{eff} = \frac{N}{1 + DF_{significant\ \ factors}}$$

n_{eff} = number of tests under that condition using the participating factors

N = number of trial in the experiment

$n_{eff} = \frac{27}{1+10} = 2.45$

Here V_e = Variance of error

$CI = \sqrt{\frac{4.23 \times 0.0026}{2.45}} = \pm\ 0.0686$

Thus the optimal value for material removal rate is 0.8482 ± 0.0686mm^3/min.

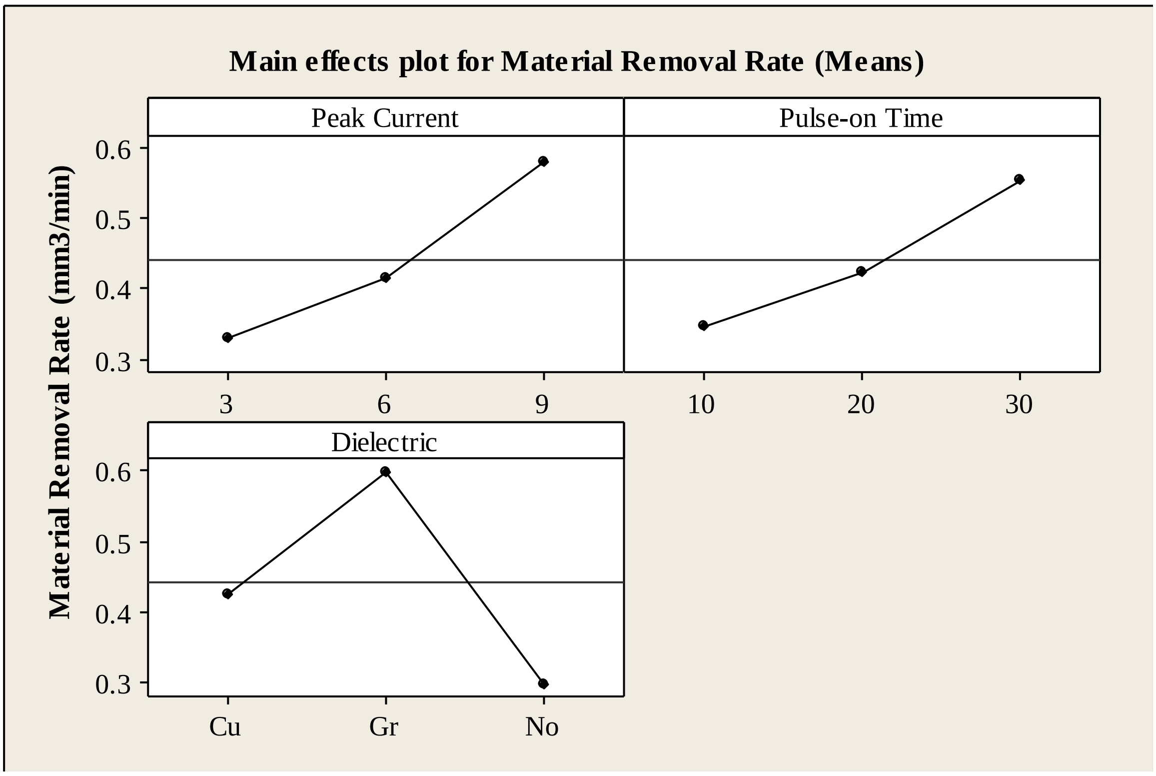


Fig. 4.2: Effect of various factors on the MRR

With the help of responses from table 4.4, graphs have been plotted by using MINITAB. Fig 4.2 shows the effect of input parameters on material removal rate. It shows the effect of various input parameters on the material removal rate. It is apparent from the graphs that MRR keeps on increasing as the peak current increases. Similar effect has been observed with pulse on-time and by using powder mixed dielectric, but the rate of increment is relatively lower than that of peak current. Powder mixed dielectric gives higher material removal rate than plain dielectric. When machining is done with graphite suspended kerosene oil, it produces better results than dielectric mixed with copper powder. The powders in kerosene oil uniformly distribute the spark energy which further increases the conductivity of dielectric fluid and improves the discharge force, thereby increasing the MRR.

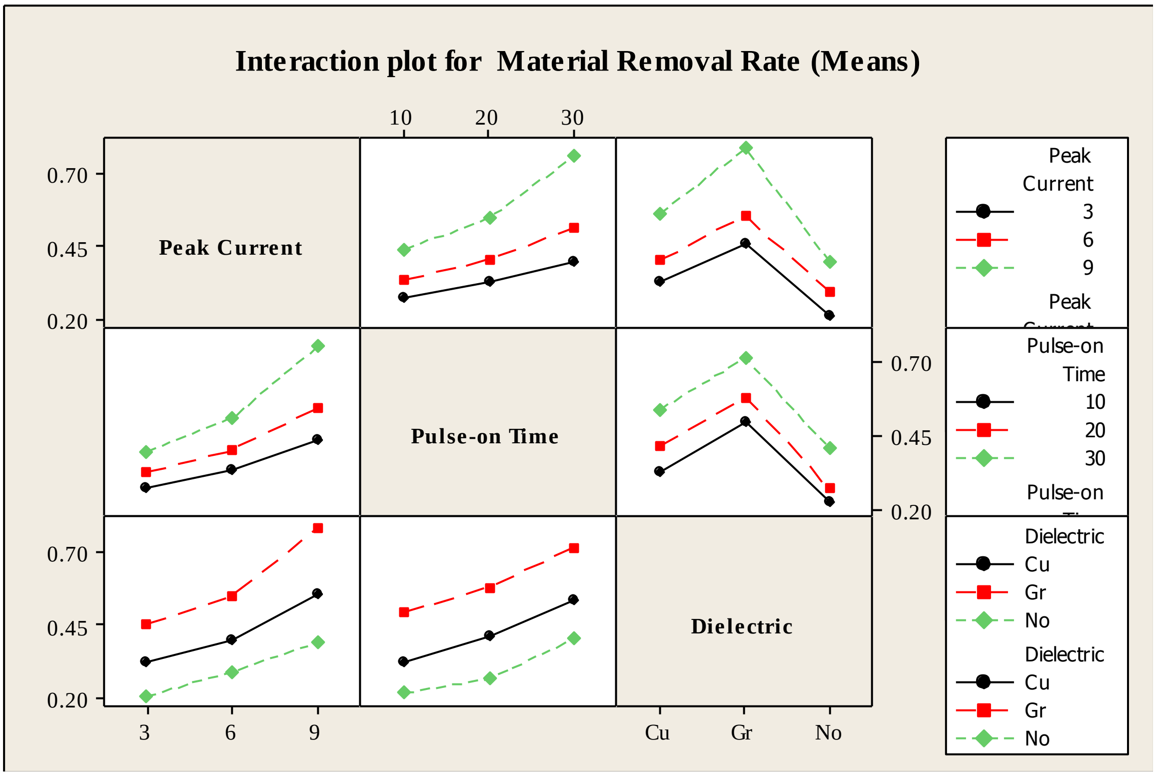


Fig. 4.3: Interaction plot for MRR

Fig. 4.3 flashes the interactive effect of all input control factors on MRR. It tells about the effect of one factor on other factor. This means that one parameter is dependent upon another factor. First graph shows the interaction between peak current and pulse on-time. Second one shows the interaction between peak current and dielectric fluid; third one shows the effect of pulse-on time and dielectric and so on. ANOVA table also established the interaction and proved by these graphs. It has been seen that graphite as additive produces better results for a particular value of peak current and pulse-on time. Maximum MRR is obtained with the combination of peak current and dielectrics. Other interactions are also available but very weak so cannot be analyzed by these figures.

4.3 Tool Wear Rate

The tool wear rate is the ratio of consumed electrode in length to the depth of drilled hole. It is the weight loss of material from the tool during machining. It decides the machining process efficiency. In this study copper is used as electrode material. Tool wear rate is calculated by taking the difference in weight before and after performing the experiment.

The tool is weighted at the well precise weighing machine after each trial. The responses with S/N ratio for tool wear rate (TWR) achieved by experiments are tabled in table.4.6 are:-

Table.4.6: Response table for Tool Wear Rate

SNo:	Peak Current	Pulse-On Time	Dielectric	TWR(mg)	S/N Ratio
1	3	10	No	15	-23.5218
2	3	10	Cu	13	-22.2789
3	3	10	Gr	10.9	-20.7485
4	3	20	No	7.2	-17.1466
5	3	20	Cu	6.8	-16.6502
6	3	20	Gr	6.4	-16.1236
7	3	30	No	3.6	-11.1261
8	3	30	Cu	3.4	-10.6296
9	3	30	Gr	3	-9.54243
10	6	10	No	14.4	-23.1672
11	6	10	Cu	11.2	-20.9844
12	6	10	Gr	9	-19.0849
13	6	20	No	10.9	-20.7485
14	6	20	Cu	8.2	-18.2763
15	6	20	Gr	7.7	-17.7298
16	6	30	No	4.8	-13.6248
17	6	30	Cu	4.3	-12.6694
18	6	30	Gr	4	-12.0412
19	9	10	No	18.6	-25.3903
20	9	10	Cu	17.5	-24.8608
21	9	10	Gr	16.9	-24.5577
22	9	20	No	17.5	-24.8608
23	9	20	Cu	12.4	-21.8684
24	9	20	Gr	11.2	-20.9844
25	9	30	No	6.1	-15.7066
26	9	30	Cu	5.4	-14.6479
27	9	30	Gr	4.9	-13.8039

With the help of above given responses, graphs have been plotted by using MINITAB. Fig 4.4 shows the effect of input parameters on tool wear rate.

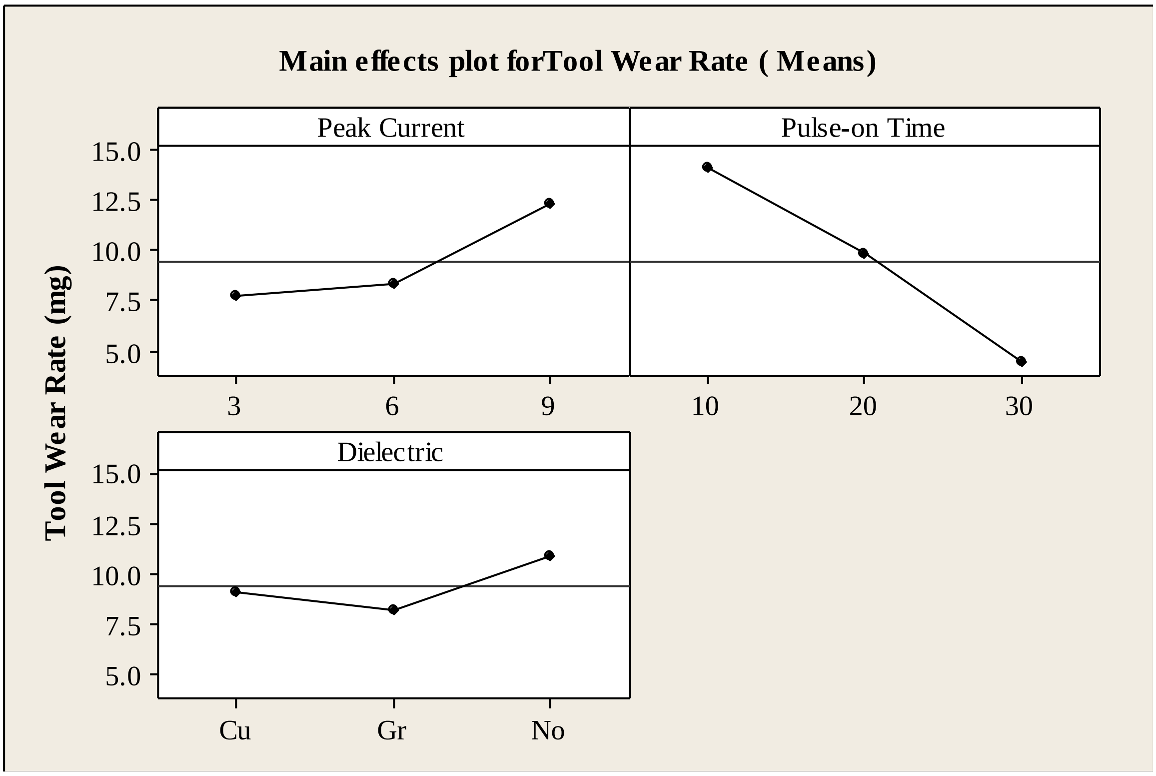


Fig. 4.4: Effect of various factors on the TWR

Fig. 4.4 indicates the impact of various input control variables i.e. peak current, pulse-on time and powder-mixed dielectric on the tool wear rate (TWR). The electrode wear is the ratio of consumed electrode in length to the depth of drilled hole. The tool material melts and gets vaporized during machining at the high temperature of sparks. It has been revealed from the above figure that tool wear rate increases with increase in peak current, but at the same time it decreases with increase in pulse-on time and when powder mixed dielectrics are used. It has also been seen that powders show better results than plain kerosene oil only. The main objective of adding powders to kerosene is to have minimum tool wear rate. Minimal tool wear is obtained by adding graphite to kerosene followed by adding copper powder.

The tool wear rate decreases by increasing pulse-on time because prolonged pulse duration would generate a large amount of carbon due to pyrolysis of kerosene oil. This pyrolytic carbon may deposit on tool cutting face to form a protective layer.

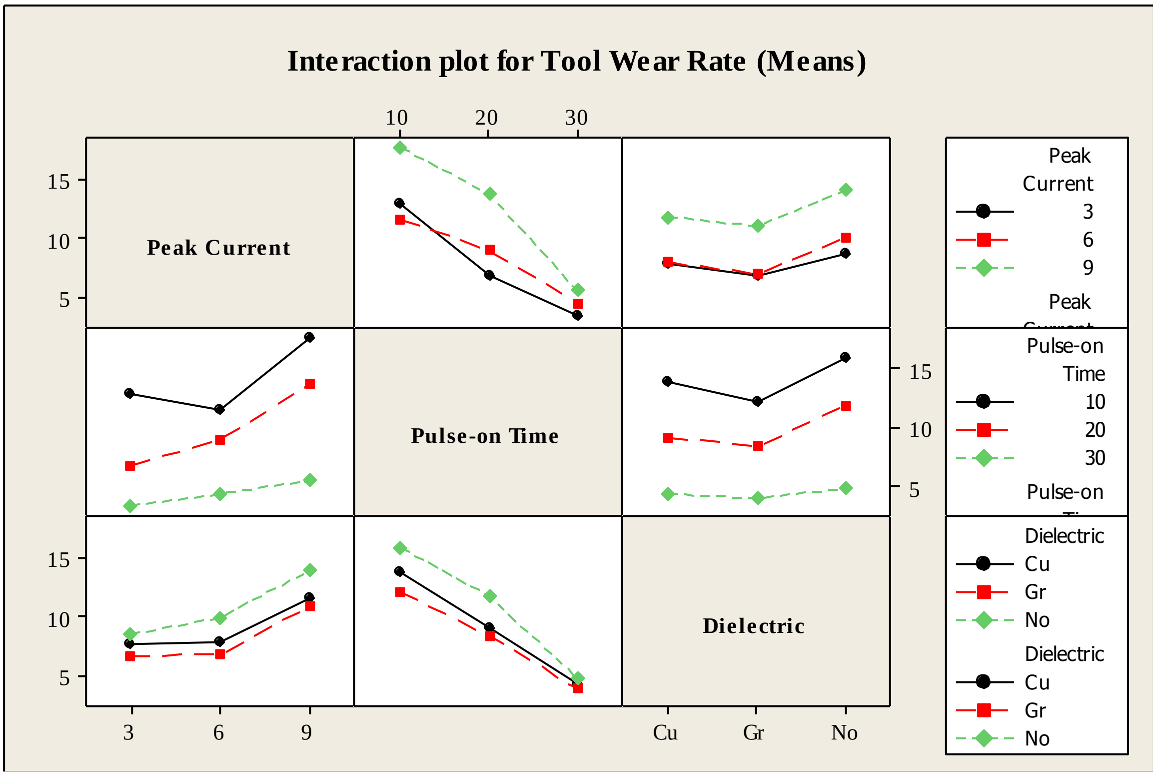


Fig. 4.5: Interaction plot for TWR

Fig. 4.5 indicates the interaction between various input control variables on the tool wear rate. It shows that combination of peak current and pulse-on-time affects the tool wear rate. It is clear observed from the graphs that when graphite is added to the kerosene, tool wear rate reduces to the minimal for a particular set of combination of current, pulse on-time and pulse off-time.

Table 4.7: ANOVA table for Tool Wear Rate

Source	**DOF**	**SS**	**Variance**	**F $_{Calculate}$**	**F $_{Table}$**	**SS'**	**C (%)**	
Peak Current (A)	2	111.870	55.935	43.53	4.46	109.23	17.60	S
Pulse On time (B)	2	422.581	211.291	164.42	4.46	419.941	67.67	S
Dielectric (C)	2	33.365	16.683	12.98	4.46	30.725	4.95	S
A XB	4	31.604	7.901	6.15	3.84	26.342	4.24	S
A X C	4	2.333	0.5833	0.45	3.84			NS
B X C	4	8.528	1.066	1.66	3.84			NS
Error	8	10.281	1.2851					
Total	26	620.561				620.561	100	
e-pooled	16	21.142	1.321			34.311	5.54	

From the ANOVA table 4.7 peak current, pulse-on time and dielectric all three input parameters has significant effect on output response. It can be clearly interpreted that interaction between peak current and pulse-on time is also significant but interactions between peak current and dielectric; pulse-on time and dielectric are insignificant because their combined effect is weak. Pulse-on time greatly influenced the tool wear rate as it starts decreasing with the increase in pulse-on time. When pulse-on time is increased from 10μs to 30 μs then the tool wear rate decreases from 15mg to 3.6mg at 3A peak current for plain dielectric. If comparison is made between different powder used i.e. without powder, graphite, copper at 3A peak current and 10μs pulse-on time then tool wear are 15mg, 13 mg and 10.9mg respectively. This means that tool wear rate decreases with the application of different types of powders. The main reason is that prolonged pulse duration would cause pyrolysis of kerosene oil due to which a large amount of carbon elements would be generated. This pyrolytic carbon may deposit on tool cutting face to form a protective layer which results decrease in tool wear. This protective layer shields the electrode surface from melting and vaporizing at high discharge energy. The increase in peak current enhances the tool wear rate because higher discharge energy may generates high temperature due to which tool face get melted and vapourized and deteriorated. As discharge energy directly depends on peak current and pulse-on time. Pulse-on time is the time for which tool and workpiece is subjected to spark energy.

Table 4.8: Average values at factor levels for Tool Wear Rate

Level	**Peak Current (A)**	**Pulse-on Time (B)**	**Dielectric (C)**
1	7.700	14.056	10.900
2	8.278	9.811	9.133
3	12.278	4.389	8.222
Delta	4.578	9.667	2.678
Rank	2	1	3

Optimal value for tool wear rate is calculated by using lower the best approach i.e. lower value is considered from each factor column. It has been perceived from the table 4.8, the minimum value of delta is 2.678 for powder mixed dielectric. So dielectric is the most significant factor for tool wear rate. For tool wear rate the optimal combination is $A_1B_3C_3$. So the optimal solution of mean of tool wear rate has been calculated.

μ_{opt} = $\bar{m}$+ (m_{A1} - $\bar{m}$) + (m_{B3} - $\bar{m}$) + (m_{C3} - $\bar{m}$)

= 9.419+ (7.700-9.419) + (4.389-9.419) + (8.222-9.419)

= 1.473 mg.

Here μ_{opt} = desired mean value

Confidence interval has also been calculated for this experimental work.

$$CI = \sqrt{\frac{F_{\alpha,v1,v2}V_e}{n_{eff}}}$$

Where $F_{\alpha, v1, v2}$ = F ratio

$\alpha = 0.05$ (risk level)

v_1 = degree of freedom for mean (always 1)

v_2 = Total degree of freedom = 26

$\bar{m}$ = average of all experiment trial

$$n_{eff} = \frac{N}{1 + DF_{significant\ \ factors}}$$

n_{eff} = number of tests under that condition using the participating factors

N = number of trial in the experiment

$n_{eff} = \frac{27}{1+10} = 2.45$

Here V_e = Variance of error

CI = $\sqrt{\frac{4.23\times0.0026}{2.45}} = \pm 1.51$

Thus the optimal value for tool wear rate is 1.473 ± 1.51mg.

4.4 Surface Roughness

It may be defined as the waviness of surface texture or the vertical deviation of real surface from ideal surface. A surface is said to rough if the waviness is more and smooth if deviation less. After performing the experiments, three readings have been taken on the surface roughness testing machine for each specimen. Signal to noise ratio is calculated by using mathematical relation i.e. the ‘Higher the Best’ approach. All three readings and their mean has been tabled in the Table.4.9.

Table.4.9: Response values for Surface Roughness

S.No.	Surface Roughness SR			SR_{mean}	S/N Ratio
	Reading_1	Reading_2	Reading_3		
1	2.09	2.28	2.35	2.24	-7.00496
2	1.98	2.15	1.93	2.02	-6.10702
3	1.82	1.66	1.71	1.73	-4.76092
4	2.35	2.76	2.93	2.68	-8.56269
5	2.26	2.21	2.04	2.17	-6.72919
6	2.21	1.82	1.88	1.97	-5.88932
7	2.82	2.76	3.06	2.88	-9.18784
8	2.65	2.59	2.5	2.58	-8.23239
9	2.05	1.97	2.46	2.16	-6.68907
10	2.98	3.06	3.08	3.04	-9.65747
11	2.93	2.54	2.81	2.76	-8.81818
12	2.67	2.59	2.51	2.59	-8.26599
13	3.37	3.43	3.82	3.54	-10.9800
14	3.04	3.34	3.13	3.17	-10.0211
15	3.14	2.87	2.81	2.94	-9.36694
16	3.58	3.99	3.44	3.67	-11.29332
17	3.18	3.33	3.54	3.35	-10.50089
18	2.95	3.1	3.16	3.07	-9.74276
19	3.64	3.92	4.11	3.89	-11.79899
20	3.48	3.71	3.88	3.69	-11.34052
21	3.42	3.58	3.56	3.52	-10.93085
22	4.09	4.12	4.18	4.13	-12.31900
23	3.84	3.96	4.38	4.06	-12.17052
24	3.72	3.91	3.98	3.87	-11.75421
25	4.52	4.18	4.44	4.38	-12.82948
26	4.12	4.14	4.19	4.15	-12.36096
27	3.82	3.97	4.18	3.99	-12.01945

Table.4.10: Design matrix and Observation table for Surface Roughness

SNo:	Peak Current	Pulse-On Time	Dielectric	SR_{mean}	S/N Ratio
1	3	10	No	2.24	-7.005
2	3	10	Cu	2.02	-6.107
3	3	10	Gr	1.73	-4.7609
4	3	20	No	2.68	-8.5627
5	3	20	Cu	2.17	-6.7292
6	3	20	Gr	1.97	-5.8893
7	3	30	No	2.88	-9.1878
8	3	30	Cu	2.58	-8.2324
9	3	30	Gr	2.16	-6.6891
10	6	10	No	3.04	-9.6575
11	6	10	Cu	2.76	-8.8182
12	6	10	Gr	2.59	-8.266
13	6	20	No	3.54	-10.98
14	6	20	Cu	3.17	-10.021
15	6	20	Gr	2.94	-9.3669
16	6	30	No	3.67	-11.293
17	6	30	Cu	3.35	-10.501
18	6	30	Gr	3.07	-9.7428
19	9	10	No	3.89	-11.799
20	9	10	Cu	3.69	-11.341
21	9	10	Gr	3.52	-10.931
22	9	20	No	4.13	-12.319
23	9	20	Cu	4.06	-12.171
24	9	20	Gr	3.87	-11.754
25	9	30	No	4.38	-12.829
26	9	30	Cu	4.15	-12.361
27	9	30	Gr	3.99	-12.019

With the help of above given responses, graphs have been plotted by using MINITAB. Fig 4.6 shows the effect of input parameters on Surface roughness.

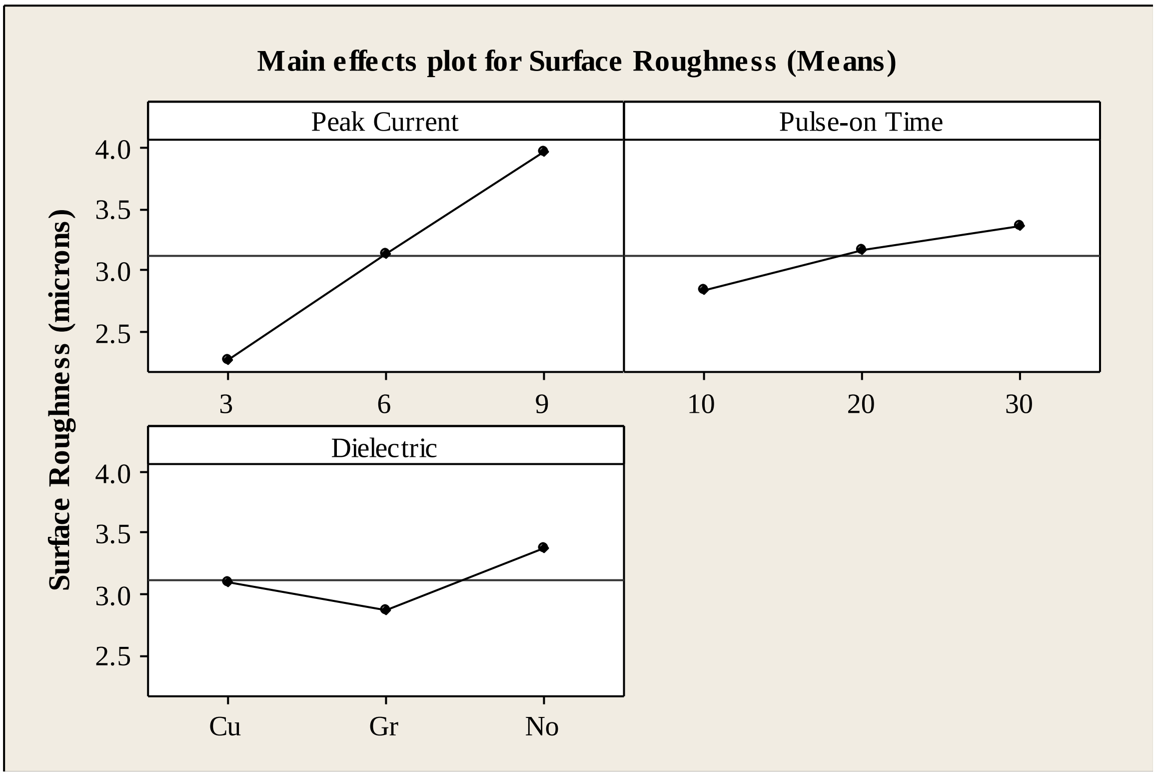


Fig. 4.6: Effect of various factors on Surface roughness

Fig. 4.6 highlights the effect of peak current, pulse-on time and dielectric on the surface finish. It indicates that surface finish deteriorates with the increase in the peak current and pulse-on time but improves with the addition of powders like copper and graphite. Best surface finish is obtained by using graphite in kerosene followed by copper. Both powder gives better surface finish than plain dielectric. The surface roughness increases sharply with increase in peak current from 3A to 9A, because higher peak current leads to high spark energy which further creates soaring impulsive force leading to higher material removal rate by removing more molten material from workpiece. Thus producing deeper and larger cavities, which reduce the surface finish. Surface roughness also increases due to pulse-on time when increased from10μs to30μs because both peak current and pulse-on time directly influences discharge energy. The reason behind the improvement of surface finish due to addition of powders in dielectric is that both powder increases the conductivity of dielectric fluid and also enhances the spark gap which helps in easy removal of debris present between the spark gap. This overall effect uniformly distributes the spark energy thereby producing smaller and shallow craters.

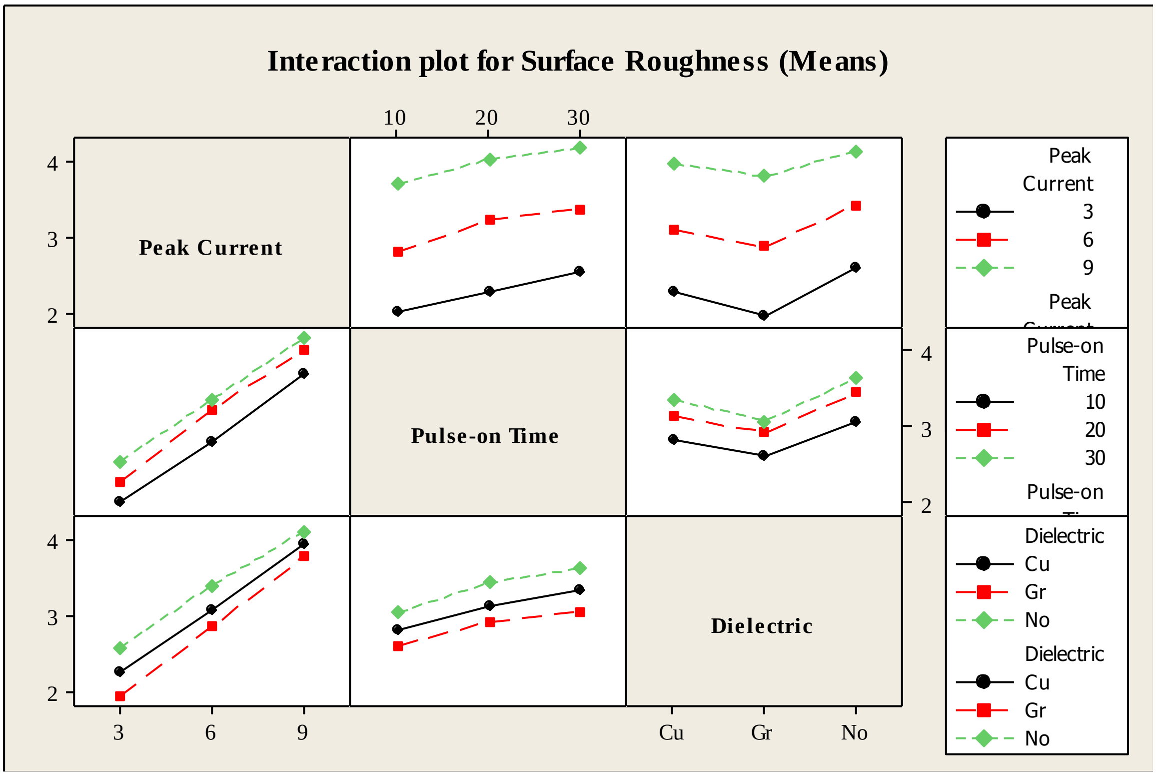


Fig. 4.7: Interaction plot for Surface roughness

Fig. 4.7 focuses on the different interaction of selected input parameters on the output variable. It indicates that combination of peak current, pulse on-time and dielectric affects the surface roughness. For lower values of current when graphite is added to the kerosene, then it gives the minimum surface roughness, but for larger values, it gives higher roughness. But on average, it gives the minimum surface roughness for a given value of current and pulse on-time.

Table 4.11: ANOVA table for Surface Roughness

Source	**DOF**	**SS**	**Variance**	**F $_{\text{Calculate}}$**	**F $_{\text{Table}}$**	**SS'**	**C (%)**	
Peak Current (A)	2	11.921	5.9605	57.26	4.46	11.821	76.06	S
Pulse-on time (B)	2	1.347	0.6735	6.47	4.46	1.247	8.02	S
Dielectric (C)	2	1.274	0.637	6.11	4.46	1.174	7.55	S
A XB	4	0.0246	0.00615	0.059	3.84			NS
A X C	4	0.1254	0.0314	0.302	3.84			NS
B X C	4	0.0158	0.00395	0.038	3.84			NS
Error	8	0.8333	0.1041					
Total	26	15.5411				15.5411	100	
e-pooled	20	0.9991	0.05			1.2991	8.37	

From the ANOVA table 4.11, it is found that surface roughness is highly affected by peak current, pulse-on time and dielectric. All these parameters come out significant. Peak current is most influential factor followed by pulse-on time and dielectric. The interaction between peak current and pulse-on time; peak current and dielectric; pulse-on time and dielectric are insignificant, as their contribution are very small so their effect is pooled in error. The main motive for optimization is to get better and smooth finish after machining process. The surface roughness increases by 74.63% when peak current is increased. On increasing pulse-on time surface finish deteriorates by 18.65%. But surface finish improves on adding powders so it improves by 8.17% for copper powder and 15.13% for graphite powder. The surface finish decreases with the increase in both peak current and pulse-on time as both of affects the spark energy. Improved surface finish can be obtained by using powders because they have a capability of evenly distributing the spark energy.

Table 4.12: Average values at factor levels for Surface roughness

Level	**Peak Current (A)**	**Pulse On time (B)**	**Dielectric (C)**
1	2.270	2.831	3.383
2	3.126	3.170	3.106
3	3.964	3.359	2.871
Delta	1.694	0.528	0.512
Rank	1	2	3

Surface roughness has been optimized by using the average values obtained from table 4.12. In this lower the best approach is applied for calculating the optimal limit. This means lower value is considered from each factor column of considered input parameters. It has been observed from the above given table the minimum value of delta is 0.512 for powder suspended dielectrics. So dielectric is the most significant factor for surface roughness. For surface roughness the optimal combination is $A_1B_1C_3$. So the optimal solution of mean of surface roughness has been calculated.

$$\mu_{opt} = \bar{m} + (m_{A1} - \bar{m}) + (m_{B3} - \bar{m}) + (m_{C3} - \bar{m})$$

$$= 3.12 + (2.270-3.12) + (2.831-3.12) + (2.871-3.12)$$

$$= 1.732 \ \mu m.$$

Here μ_{opt} = desired mean value

Confidence interval has also been calculated for this experimental work.

$$CI = \sqrt{\frac{F_{\alpha,v1,v2}V_e}{n_{eff}}}$$

Where $F_{\alpha,\ v1,\ v2}$ = F ratio

$\alpha = 0.05$ (risk level)

v_1 = degree of freedom for mean (always 1)

v_2 = Total degree of freedom = 26

$\bar{m}$ = average of all experiment trial

$$n_{eff} = \frac{N}{1 + DF_{significant\quad factor\ s}}$$

n_{eff} = number of tests under that condition using the participating factors

N = number of trial in the experiment

$n_{eff} = \frac{27}{1+6} = 3.86$

Here V_e = Variance of error

$CI = \sqrt{\frac{4.23\times0.05}{2.45}} = \pm\ 0.055$

Thus the optimal value for surface roughness is 1.732 ± 0.055 µm.

4.5 Micro hardness

Micro-hardness testing is a technique designed for evaluating the surface hardness of a material on a microscopic scale. All EDM processed samples were undertaken to micro-hardness testing using a load of 1000 g for a duration time of 20 seconds. The micro hardness of parent metal measured as 332hv. Micro hardness is improved by considerable amount for all samples after EDM machining. More than 100% increase in micro-hardness is observed for all the samples.

.After performing the experiments, three readings has been taken on the hardness testing machine for each specimen. All three readings and their mean were tabled in the Table.4.13. Signal to noise ratio is calculated by using mathematical relation i.e. the ‘Higher the Best’ approach has already been described earlier.

Table.4.13: Response values for Micro-hardness

S.No.	Micro hardness			Micro hardness$_{mean}$ (y_{mean})	S/N Ratio
	Reading 1	Reading 2	Reading 3		
1	684.5035	683.393	684.9234	684.2733	56.7045
2	723.4992	729.2445	723.851	725.5315	57.2131
3	779.631	779.631	773.76	777.674	57.8159
4	696.2661	696.1598	696.266	696.2306	56.8550
5	740.6893	741.76	741.2992	741.2495	57.3992
6	806.5129	805.379	805.379	805.7569	58.1240
7	735.7172	735.5035	729.2245	733.4817	57.3077
8	788.0178	790.266	787.1598	788.4812	57.9358
9	842.1163	842.1163	842.1163	842.1163	58.5074
10	769.1537	760.342	773.76	767.7519	57.7044
11	820.4782	821.4782	819.0178	820.3247	58.2797
12	888.0417	887.8226	890.2661	888.7101	58.9752
13	812.2939	805.379	820.4782	812.7170	58.1987
14	871.359	871.359	871.359	871.359	58.8039
15	929.2447	929.2974	928.5973	929.0464	59.3607
16	859.6223	853.6913	845.2245	852.8460	58.6174
17	927.5973	926.917	926.0178	926.8440	59.3401
18	946.5326	942.5326	948.3738	945.813	59.5161
19	887.8226	888.0417	890.2661	888.7101	58.9752
20	955.3958	954.9952	955.3958	955.2622	59.6024
21	991.9234	991.9234	991.9234	991.9234	59.9295
22	912.645	919.2447	912.8293	914.9063	59.2275
23	977.6799	977.6799	976.2992	977.2196	59.7998
24	1071.645	1072.9243	1072.939	1072.5027	60.6079
25	942.6913	946.5326	944.3738	944.53256	59.5043
26	1030.629	1030.625	1030.629	1030.6276	60.2620
27	1115.159	1115.159	1116.4782	1115.5987	60.9501

Table.4.14: Design matrix and Observation table for Micro-hardness

S.No:	**Peak Current**	**Pulse-On Time**	**Dielectric**	**y_{mean}**	**S/N Ratio**
1	3	10	No	684.273	56.7045
2	3	10	Cu	725.532	57.2131
3	3	10	Gr	777.674	57.8159
4	3	20	No	696.231	56.855
5	3	20	Cu	741.25	57.3992
6	3	20	Gr	805.757	58.124
7	3	30	No	733.482	57.3077
8	3	30	Cu	788.481	57.9358
9	3	30	Gr	842.116	58.5074
10	6	10	No	767.752	57.7044
11	6	10	Cu	820.325	58.2797
12	6	10	Gr	888.71	58.9752
13	6	20	No	812.717	58.1987
14	6	20	Cu	871.359	58.8039
15	6	20	Gr	929.046	59.3607
16	6	30	No	852.846	58.6174
17	6	30	Cu	926.844	59.3401
18	6	30	Gr	945.813	59.5161
19	9	10	No	888.71	58.9752
20	9	10	Cu	955.262	59.6024
21	9	10	Gr	991.923	59.9295
22	9	20	No	914.906	59.2275
23	9	20	Cu	977.22	59.7998
24	9	20	Gr	1072.5	60.6079
25	9	30	No	944.533	59.5043
26	9	30	Cu	1030.63	60.262
27	9	30	Gr	1115.6	60.9501

With the help of above given responses, graphs have been plotted by using MINITAB. Fig 4.8 shows the effect of input parameters on Surface roughness.

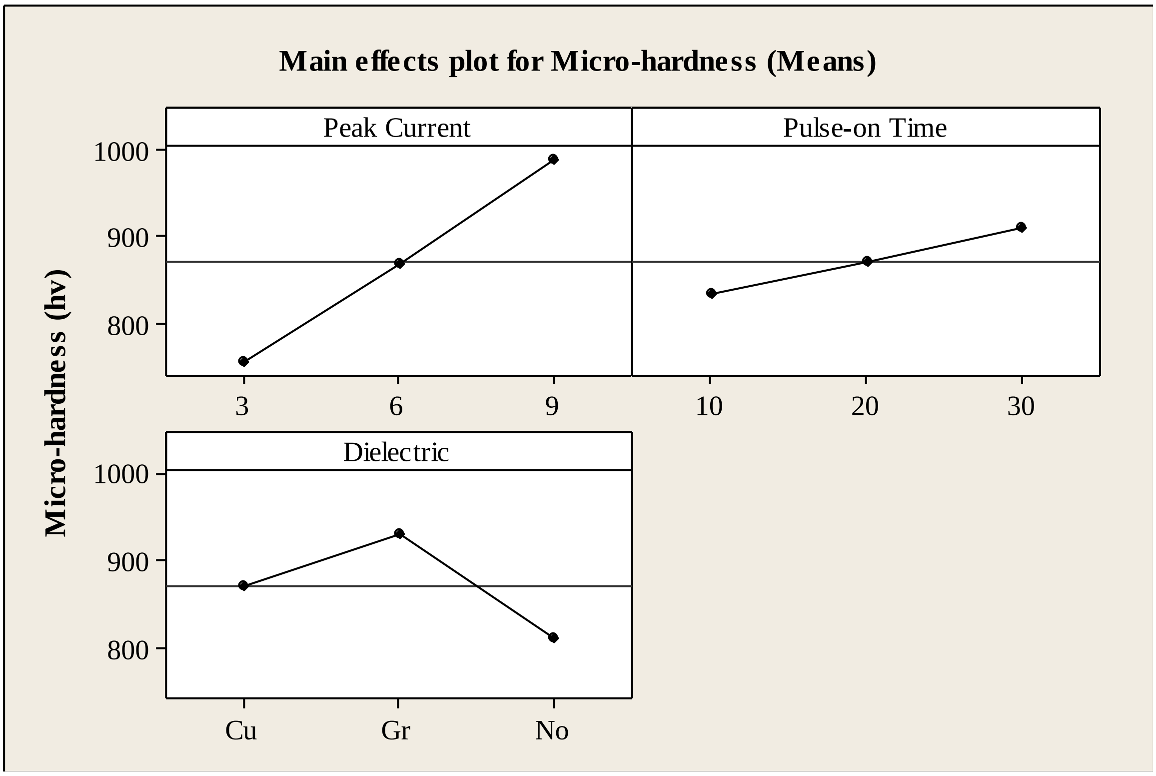


Fig. 4.8: Effect of various factors on Micro-hardness

Fig. 4.8 reports the influence of various considered input parameters on output responses i.e. micro-hardness. The micro-hardness increases with increases in peak current and pulse-on time. It increases sharply with the effect of peak current but in case of pulse-on time it increases at slower incremental rate. Higher peak current and pulse-on time leads to higher discharge energy that generates more heat and results in the increase of surface hardness. This may be due the repetitive cyclic heating which makes the spark surface hot and cool immediately by the dielectric fluid. These figures show that powder mixed dielectric gives better output than without powder. Maximum hardness is obtained by suspending graphite power followed by copper powder. It is due to reason that hydrocarbon dielectric fluid under goes the pryolysis thus generating carbon pickups. These carbon particles get migrated into workpiece surface during pulse-off duration. The carbon particle tries to form intermetallic compounds with titanium to form cabides or alloyed cementite. Such type of formed compound significantly increases the micro hardness. These formations caused significant increase in micro-hardness.

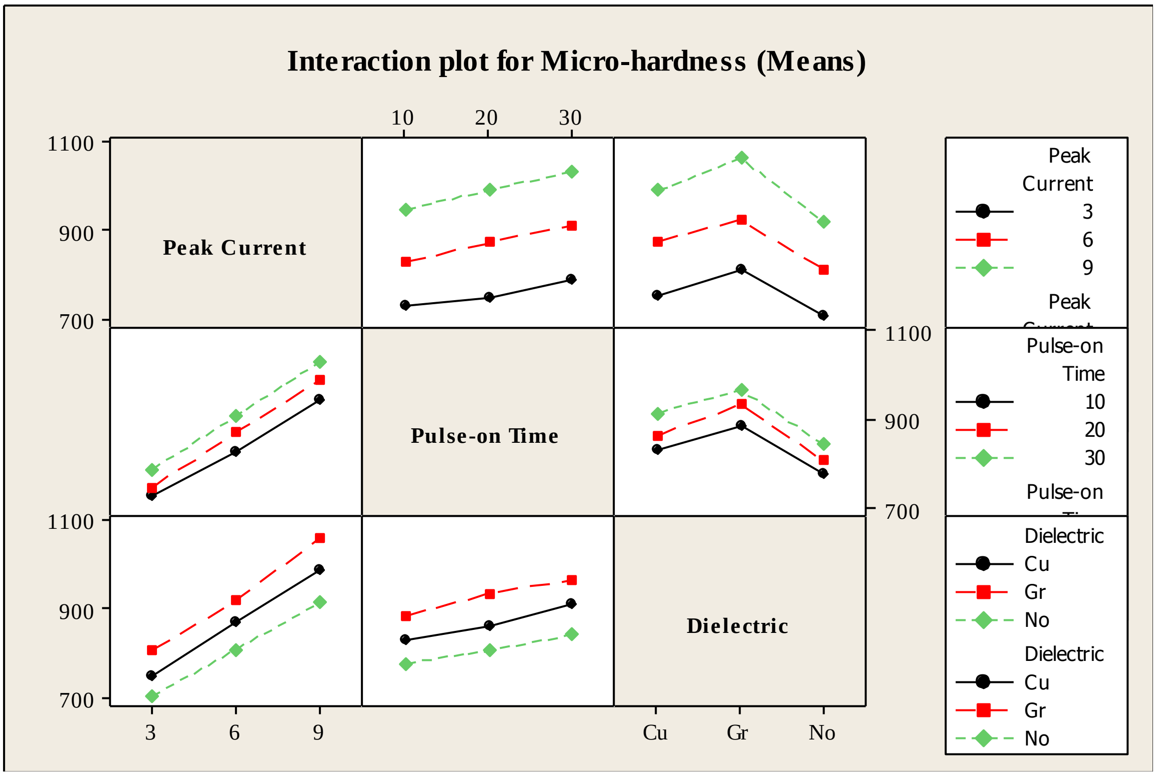


Fig. 4.9: Interaction plot for Micro-hardness

Fig. 4.9 reflects the different interactions of input parameters on micro-hardness. It is clearly analyzed from the graph that micro-hardness increases with the increase in peak current, pulse-on time and with the\addition of powder.

Table 4.15: ANOVA table for Micro-hardness

Source	DOF	SS	Variance	F Calculate	F Table	SS'	C (%)	
Peak Current (A)	2	234238	117119	80.25	4.46	232756	68.69	S
Pulse On time (B)	2	25730	12865	8.82	4.46	24248	7.16	S
Dielectric (C)	2	64047	32023.5	21.94	4.46	58565	17.28	S
A XB	4	871	217.75	0.149	3.84			NS
A X C	4	1532	383	1.05	3.84			NS
B X C	4	746	186.5	0.51	3.84			NS
Error	8	11675	1459.375					
Total	26	338840				338840	100	
e-pooled	20	14824	741.2			23271	6.85	

From the ANOVA table 4.15, it is clearly interpreted that all three parameters are significant but no interaction is significant. Micro-hardness is highly affected by peak current followed by dielectric and pulse-on time. Interactions are affecting the machining process at very low level; their effects are actually insignificant and pooled in error. From average value table it has been found that micro hardness for peak current increases by 30.84%. In case of pulse-on time it increases by 9.07%. When it is analyzed for powders then the percentage increase in micro hardness is found as 7.43% and 14.72% for copper mixed kerosene oil and graphite mixed kerosene oil respectively. The percentage increase in micro hardness when compared with mixed kerosene oil and graphite mixed kerosene oil is 6.81%. Powder mixed in dielectric fluid increases the conductivity by weakening the dielectric strength of fluid, which increases the heat generation on workpiece causing repetitive cyclic heating which makes the spark surface hot and cool immediately by the dielectric fluid. The heat generation also leads to pryolysis of kerosene oil that helps in generating numerous amounts of carbon particles which get migrated into workpiece surface during pulse-off duration. The migrated particles forms titanium compounds like carbides i.e. TiC or alloyed cementite. Formation of titanium compounds increases micro-hardness. It can be further increased by increasing carbon content up to a specific limit.

Table 4.16: Average values at factor levels for Micro-hardness

Level	**Peak Current (A)**	**Pulse On time (B)**	**Dielectric (C)**
1	755.0	833.4	810.6
2	868.4	869.0	870.8
3	987.9	908.9	929.9
Delta	232.9	75.6	119.3
Rank	1	2	3

Table 4.16 shows the average values at factor levels for micro-hardness and the maximum value of delta is 232.9. So peak current is the most significant factor. In this case the goal of the study is to have maximum micro hardness. As all three input factors are contributing differently, so in order to obtain maximum results an optimal solution has been calculated. $A_3B_3C_3$ is the optimal combination in case of micro hardness. So the calculated optimal solution for mean of micro hardness is as shown under.

μ_{opt} = $\bar{m}$+ (m_{A3} - $\bar{m}$) + (m_{B3} - $\bar{m}$) + (m_{C3} - $\bar{m}$)

= 870.433+ (987.9-870.433) + (908.9-870.433) + (929.9-870.433)

= 1085.834 hv.

Here μ_{opt} = desired mean value

Confidence interval has also been calculated for this experimental work.

$$CI = \sqrt{\frac{F_{\alpha,v1,v2}V_e}{n_{eff}}}$$

Where $F_{\alpha,\, v1,\, v2}$ = F ratio

α = 0.05 (risk level)

v_1 = degree of freedom for mean (always 1)

v_2 = Total degree of freedom = 26

$\bar{m}$ = average of all experiment trial

$$n_{eff} = \frac{N}{1 + DF_{significan\ t\ factors}}$$

n_{eff} = number of tests under that condition using the participating factors

N = number of trial in the experiment

$n_{eff} = \frac{27}{1+6} = 3.86$

Here V_e = Variance of error

$CI = \sqrt{\frac{4.23 \times 0.05}{2.45}} = \pm 28.50$

Thus the optimal value for micro hardness is 1085.834 ± 28.50 μm.

4.6 Multi-response optimization by using Grey Relational Analysis

Multi-response optimization techniques are used where different response or outcomes of a particular sample at same input parameter level are known. There are different methods of multi-response optimization technique like fuzzy logic, grey relation analysis etc. Grey relation analysis is used in this study.

4.6.1 Grey relation analysis

Grey relational analysis is used to find the optimal result from the given trial conditions. It is used when there are different response quality parameters. This methodology converts the different objective quality parameters into single objective quality parameter. This methodology converts the different responses into single grey grade. The grey relational grade which has maximum value is the optimal result for different responses.

The following steps are used in grey relational analysis.

1. Find out the experimental results of DOE.
2. Normalize the results in the domain of (0, 1) by using (4.1) and (4.2) equation.

- For higher the better result

$N_{ij} = [X_{ij} – (X_{ij})_{min}] / [(X_{ij})_{max} – (X_{ij})_{min}]$……………………..….. Eq. (4.1)

- For lower the better result

$N_{ij} = [(X_{ij})_{max} – X_{ij}] / [(X_{ij})_{max} – (X_{ij})_{min}]$………….. ……..…….Eq. (4.2)

Where N_{ij} = normalized value

$(X_{ij})_{max}$ = maximum value of response parameter

$(X_{ij})_{min}$ = minimum value of response parameter

X_{ij} = value of response in i column and j row matrix

3. Calculate $\Delta_{ij} = |X_{oj} - X_{ij}|$ ……………..……..… Eq. (4.3)

   Where Δ_{ij} is the absolute value of difference in X_{oj} and X_{ij}

4. Calculate grey relation co- efficient by using equation (c)

   $Y(X_{oj}, X_{ij}) = \frac{\Delta_{min} + \varepsilon\, \Delta_{max}}{\Delta_{ij} + \varepsilon\, \Delta_{maxj}}$ ……………………..Eq. (4.4)

   Where Y = grey relation co-efficient

   ε = distinguish factor between 0 and 1. Here it is taken as 0.5

5. After calculating grey relation co- efficient, calculate grey relational grade by taking the average value of grey co- efficient.

4.6.2 Implementation of Grey analysis

Step 1: Results for material removal rate, tool wear rate, surface roughness and microhardness are obtained for the trial conditions as shown in Table 4.17.

Table 4.17: Various responses for trial conditions

SNo :	Peak Current	Pulse-On Time	Dielectric	MRR	TWR	Surface Roughness	Micro Hardness
1	3	10	No	0.1717	15	2.24	684.273
2	3	10	Cu	0.2648	13	2.02	725.532
3	3	10	Gr	0.3744	10.9	1.73	777.674
4	3	20	No	0.192	7.2	2.68	696.231
5	3	20	Cu	0.3182	6.8	2.17	741.25
6	3	20	Gr	0.4644	6.4	1.97	805.757
7	3	30	No	0.2691	3.6	2.88	733.482
8	3	30	Cu	0.3889	3.4	2.58	788.481
9	3	30	Gr	0.5344	3	2.16	842.116
10	6	10	No	0.2294	14.4	3.04	767.752
11	6	10	Cu	0.3054	11.2	2.76	820.325
12	6	10	Gr	0.471	9	2.59	888.71
13	6	20	No	0.2667	10.9	3.54	812.717
14	6	20	Cu	0.382	8.2	3.17	871.359
15	6	20	Gr	0.5561	7.7	2.94	929.046
16	6	30	No	0.3835	4.8	3.67	852.846
17	6	30	Cu	0.514	4.3	3.35	926.844
18	6	30	Gr	0.6346	4	3.07	945.813
19	9	10	No	0.2648	18.6	3.89	888.71
20	9	10	Cu	0.4008	17.5	3.69	955.262
21	9	10	Gr	0.6441	16.9	3.52	991.923
22	9	20	No	0.3542	17.5	4.13	914.906
23	9	20	Cu	0.552	12.4	4.06	977.22
24	9	20	Gr	0.7281	11.2	3.87	1072.5
25	9	30	No	0.5655	6.1	4.38	944.533
26	9	30	Cu	0.7177	5.4	4.15	1030.63
27	9	30	Gr	0.9819	4.9	3.99	1115.6

Step 2: Calculate the normalized value for each response by using equations 4.1 and 4.4. For material removal rate and microhardness ‘Higher the better’ condition is used. For tool wear rate and surface roughness ‘lower the better’ condition is used. Normalization (N) of various responses is shown in Table 4.18.

Table 4.18: Normalization table for various responses

SNo:	**Peak Current**	**Pulse-On Time**	**Dielectric**	**MRR (N)**	**TWR (N)**	**Surface roughness**	**Micro-Hardness(N)**
1	3	10	No	0	0.2307	0.8075	0
2	3	10	Cu	0.115	0.359	0.8906	0.0957
3	3	10	Gr	0.2502	0.4936	1	0.2165
4	3	20	No	0.0251	0.7308	0.6415	0.0277
5	3	20	Cu	0.1808	0.7564	0.834	0.1321
6	3	20	Gr	0.3613	0.7821	0.9094	0.2817
7	3	30	No	0.1202	0.9615	0.566	0.1141
8	3	30	Cu	0.2681	0.9744	0.6792	0.2416
9	3	30	Gr	0.4477	1	0.8377	0.0414
10	6	10	No	0.0712	0.2692	0.5057	0.1935
11	6	10	Cu	0.165	0.4736	0.6113	0.3154
12	6	10	Gr	0.3694	0.6154	0.6755	0.474
13	6	20	No	0.1172	0.4936	0.317	0.2978
14	6	20	Cu	0.2596	0.6667	0.4566	0.4338
15	6	20	Gr	0.4745	0.6987	0.5434	0.5675
16	6	30	No	0.2614	0.8846	0.2679	0.3908
17	6	30	Cu	0.4225	0.9167	0.3887	0.5624
18	6	30	Gr	0.5713	0.9359	0.4943	0.6064
19	9	10	No	0.115	0	0.1849	0.474
20	9	10	Cu	0.2828	0.0705	0.2604	0.6283
21	9	10	Gr	0.5831	0.109	0.3245	0.7133
22	9	20	No	0.2253	0.0705	0.0943	0.5348
23	9	20	Cu	0.4694	0.3974	0.1208	0.6792
24	9	20	Gr	0.6867	0.4744	0.1925	0.9001
25	9	30	No	0.4861	0.8013	0	0.6034
26	9	30	Cu	0.6739	0.8462	0.0868	0.803
27	9	30	Gr	1	0.8782	0.1472	1

Step 3: Calculate Δ_{ij} values for all output responses by using equation 4.3 discussed in section 4.6.1. The values of Δ for different responses have been reported in Table 4.19.

Table 4.19: Δ value for various responses

SNo:	**Peak Current**	**Pulse-On Time**	**Dielectric**	**MRR (Δ)**	**TWR (Δ)**	**Surface roughness (Δ)**	**Micro-Hardness (Δ)**
1	3	10	No	1	0.7693	0.1925	1
2	3	10	Cu	0.885	0.641	0.1094	0.9043
3	3	10	Gr	0.7498	0.5064	0	0.7835
4	3	20	No	0.9749	0.2692	0.3585	0.9723
5	3	20	Cu	0.8192	0.2436	0.166	0.8679
6	3	20	Gr	0.6387	0.2179	0.0906	0.7183
7	3	30	No	0.8798	0.0385	0.434	0.8859
8	3	30	Cu	0.7319	0.0256	0.3208	0.7584
9	3	30	Gr	0.5523	0	0.1623	0.9586
10	6	10	No	0.9288	0.7308	0.4943	0.8065
11	6	10	Cu	0.835	0.5264	0.3887	0.6846
12	6	10	Gr	0.6306	0.3846	0.3245	0.526
13	6	20	No	0.8828	0.5064	0.683	0.7022
14	6	20	Cu	0.7404	0.3333	0.5434	0.5662
15	6	20	Gr	0.5255	0.3013	0.4566	0.4325
16	6	30	No	0.7386	0.1154	0.7321	0.6092
17	6	30	Cu	0.5775	0.0833	0.6113	0.4376
18	6	30	Gr	0.4287	0.0641	0.5057	0.3936
19	9	10	No	0.885	1	0.8151	0.526
20	9	10	Cu	0.7172	0.9295	0.7396	0.3717
21	9	10	Gr	0.4169	0.891	0.6755	0.2867
22	9	20	No	0.7747	0.9295	0.9057	0.4652
23	9	20	Cu	0.5306	0.6026	0.8792	0.3208
24	9	20	Gr	0.3133	0.5256	0.8075	0.0999
25	9	30	No	0.5139	0.1987	1	0.3966
26	9	30	Cu	0.3261	0.1538	0.9132	0.197
27	9	30	Gr	0	0.1218	0.8528	0

Step 4: After finding Δ, grey relation coefficient(Y) has been calculated by using equation 4.4. Its values for different responses are shown in Table 4.20

Table 4.20: Grey relation coefficient for various trials

SNo:	**Peak Current**	**Pulse-On Time**	**Dielectric**	**MRR (Y)**	**TWR (Y)**	**Surface roughness (Y)**	**Micro-Hardness (Y)**
1	3	10	No	0.3333	0.3939	0.7220	0.3333
2	3	10	Cu	0.3610	0.4382	0.8205	0.3561
3	3	10	Gr	0.4001	0.4968	1	0.3896
4	3	20	No	0.3390	0.6500	0.5824	0.3396
5	3	20	Cu	0.3790	0.6724	0.7508	0.3655
6	3	20	Gr	0.4391	0.6965	0.8466	0.4104
7	3	30	No	0.3624	0.9285	0.5353	0.3608
8	3	30	Cu	0.4059	0.9513	0.6092	0.3973
9	3	30	Gr	0.4752	1	0.7549	0.3428
10	6	10	No	0.3499	0.4062	0.5029	0.3827
11	6	10	Cu	0.3745	0.4871	0.5626	0.4221
12	6	10	Gr	0.4422	0.5652	0.6064	0.4873
13	6	20	No	0.3616	0.4968	0.4227	0.4159
14	6	20	Cu	0.4031	0.6000	0.4792	0.4689
15	6	20	Gr	0.4876	0.6234	0.5227	0.5362
16	6	30	No	0.4037	0.8125	0.4058	0.4508
17	6	30	Cu	0.4640	0.8572	0.4499	0.5333
18	6	30	Gr	0.5384	0.8864	0.4972	0.5595
19	9	10	No	0.3610	0.3333	0.3802	0.4873
20	9	10	Cu	0.4108	0.3498	0.4034	0.5736
21	9	10	Gr	0.5453	0.3595	0.4254	0.6356
22	9	20	No	0.3922	0.3498	0.3557	0.5180
23	9	20	Cu	0.4852	0.4535	0.3625	0.6092
24	9	20	Gr	0.6148	0.4875	0.3824	0.8335
25	9	30	No	0.4932	0.7156	0.3333	0.5577
26	9	30	Cu	0.6053	0.7648	0.3538	0.7174
27	9	30	Gr	1	0.8041	0.3696	1

Step 5: Grey relation grade is calculated by taking the average of all grey relation coefficient and then ranking the each trial according to Grey relation grade. Table 4.21 shows the different input parameters value with corresponding grey grade.

Table 4.21: Grey relation grade at different parameters level

S.No.	**Peak Current**	**Pulse-On Time**	**Dielectric**	**Grey relation grade**	**Rank**
1	3	10	No	0.4457	22
2	3	10	Cu	0.4939	16
3	3	10	Gr	0.5716	9
4	3	20	No	0.4778	19
5	3	20	Cu	0.5419	12
6	3	20	Gr	0.5981	5
7	3	30	No	0.5467	10
8	3	30	Cu	0.5909	6
9	3	30	Gr	0.6432	2
10	6	10	No	0.4104	25
11	6	10	Cu	0.4616	21
12	6	10	Gr	0.5253	13
13	6	20	No	0.4242	24
14	6	20	Cu	0.4878	18
15	6	20	Gr	0.5426	11
16	6	30	No	0.5182	15
17	6	30	Cu	0.5761	8
18	6	30	Gr	0.6204	3
19	9	10	No	0.3905	27
20	9	10	Cu	0.4344	23
21	9	10	Gr	0.4914	17
22	9	20	No	0.4039	26
23	9	20	Cu	0.4776	20
24	9	20	Gr	0.5795	7
25	9	30	No	0.5249	14
26	9	30	Cu	0.6103	4
27	9	30	Gr	0.7934	1

Table 4.21 indicates the ranks of different trails that are found by grey relation analysis. The optimal result from different parameter of three levels each for different responses is trial condition 27 which has a highest value of 0.7934. With the help of this analysis, different parameters can be compared with the help of grey relational grade for multi objective responses. This specific trial has maximum material removal rate, micro-hardness along with desirable surface finish and low tool wear rate. During machining of this experiment peak current and pulse-on time are 9 A, 30 µs respectively which means higher amperage generates high discharge energy for longer pulse duration and graphite mixed kerosene as dielectric fluid increases the spark gap along with uniform distribution of spark energy, which leads to increase in material removal rate and better surface finish. At increased pulse-on time pyrolysis of kerosene oil takes place, due to which a large amount of carbon elements are released, that adheres with the surface of the electrode and form a protective layer, so lower the tool wear rate. At the same time these released carbon elements also migrates into the surface of machined thereby forming carbides i.e. TiC. This results in increase in micro-hardness.

Table 4.22: Average values at factor levels for Grey Relational Grade

Level	**Peak Current**	**Pulse-On time**	**Dielectric**
1	0.5455	0.4694	0.5194
2	0.5074	0.5037	0.5962
3	0.5229	0.6027	0.4603
Delta	0.0381	0.1333	0.1359
Rank	3	2	1

Table 4.22 shows the mean of the grey relational grade for each level of the process parameters. The larger the mean of the grey relational grade, the better is the multiple process response. The mean of grey relational grade is 0.525.

Whole experiment has been designed according to L27 orthogonal array (Taguchi method). So it becomes feasible to separate out the effect of each process input factor at different levels. ANOVA has been used to study which input process variables significantly affect the process output response. This can be achieved by separating the total variability of the grey relational grade, by calculating sum of square which means deviations from total mean, percentage contribution of each input parameter and error.

Table 4.23: ANOVA table for Grey Relational Grade

Source	**DOF**	**SS**	**Variance**	**F_{test}**	**Contribution (%)**
Peak Current (A)	2	0.006621	0.003310	2.45	3.25
Pulse-On Time (B)	2	0.086182	0.043091	31.84	42.56
Dielectric (C)	2	0.083590	0.041795	30.89	41.08
Residual Error	20	0.027065	0.001353		
Total	26	0.203457			

ANOVA table 4.23 shows that pulse-on time and dielectric are most significant factor and their percentage contribution is 31.84% and 30.89% respectively. In this multi response optimization process two input variables i.e. pulse-on time and dielectric are of great importance.

CHAPTER 5

CONCLUSION

This chapter covers the summary and conclusion of the experimental work being performed on EDM machine and tests conducted on the surface roughness tester and micro-hardness tester. This also highlights shortcoming of the present study and scope of the future research that can be performed.

5.1 Conclusion

The experiments were performed on EDM machine for different parameters at three levels. Taguchi method has been used to optimize the machining performance variables. it is used to optimize the single outcome. The different outcomes of the experiment were utilized for the optimization study. For different outcomes, the best result for the experimental setup has been found by using Grey relation analysis. Some of the important features were observed during EDM which is discussed in this section.

1) Maximum material removal rate is obtained at a high peak current of 9A, a high pulse-on time and with graphite powder. All three selected parameters affect the MRR significantly. MRR increases when peak current and pulse-on time is increased. Higher MRR is also obtained when powders are suspended in dielectric fluid.
2) Low tool wear rate is obtained with low peak current of 3A, high pulse-on time of 30µs and with graphite powder. Tool wear rate decreases with increase in pulse-on time and by using powders in dielectric. It increases with increase in peak current. Powders give better results than plain kerosene oil.
3) Surface roughness increases with increase in peak current and pulse-on time. Improved surface finish is obtained by adding graphite powder in dielectric followed by copper powder. High surface finish is achieved when machining is performed at 3A peak current, 10µs pulse-on time and with graphite powder.
4) Peak current is the most influential factor for micro hardness. High micro hardness is obtained at 9A peak current, 30µs pulse-on time and by using graphite powder. When peak current and pulse-on time is increased then micro hardness also increases. Micro hardness increases more than 100% after sample is

processed by EDM process. The optimal value for micro hardness is 1085.834 ± 28.50 μm.

5) From grey relation analysis has been used to obtain the best result for multi-response outputs. The best optimal solution has been found in experiment trial no.27 which has three input parameters i.e. peak current at 9A, pulse-on time at 30μs and with graphite mixed dielectric. This particular run has highest material removal rate and micro hardness from all other experiment run. By using ANOVA it has been found that pulse-on time as more significant effect on process machining output.

5.2 **Scope for Future work**

1) In this study polarity is set as straight polarity, this can be reversed and their effect on machining parameter must be studied.
2) A number of other electrode materials such as graphite, brass, composites etc. are available that can be applied for future work.
3) Single copper electrode has been used in the study; bundled electrode of different materials may be used for forecoming research.
4) Different powders such as graphite, copper, aluminium, Sic, B_4C are used in previous works with Ti-6Al-4V. In this work, copper and graphite powders have been used. Other powders such as nickel, titanium, vanadium etc. which may be used in future works.
5) The debris which is left in the dielectric must be analyzed to observe the outcome.
6) In most of researches of Ti-6Al-4V, researchers used (de-ionized water+ B4C), (distilled water + Sic), (kerosene oil +Al) and (kerosene oil + B4C) as dielectrics. In present work combinations of (Kerosene oil + Cu) and (Kerosene oil + Gr) are used. Other combinations can be used.
7) Surface response methodology and Taguchi method is widely used but grey relational analysis method and Fuzzy logic etc. may be applied to future works.

REFERENCES

1) Choudhary S K and Jadoun R.S., “Current Advanced Research Development of Electric Discharge Machining (EDM): A Review”, International Journal of Research in Advent Technology, Vol.2, No.3, March 2014 ,E-ISSN: 2321-9637.
2) Singh S. and Bhardwaj A., “Review to EDM by Using Water and Powder-Mixed Dielectric Fluid”,Vol. 10, No.2, (2011) pp.199-230.
3) Kibria G., Sarkar B. R., Pradhan B. B., LinY C. and, Lee H., and Bhattacharyya B., “Comparative study of different dielectrics for micro-EDM performance during micro hole machining of Ti-6Al-4V alloy”, Int J Adv Manuf Technology (2010) 48:557–570.
4) Zhang Y. , Liu Y. , Shen Y. , Ji R., Li Z. and Zheng C., “Investigation on the influence of the dielectrics on the material removal characteristics of EDM”, Journal of Materials Processing Technology 214 (2014) 1052– 1061.
5) Lin Y C. and, Lee H.,“Machining characteristics of magnetic force-assisted EDM”, International Journal of Machine Tools & Manufacture 48 (2008) 1179–1186.
6) Lin Y C., Yan B H. and Chang Y S., “Machining characteristics of titanium alloy (Ti-6Al-4V) using a combination process of EDM with USM” Journal of Materials Processing Technology 104 (2000) 171-177.
7) Singh S K.and Kumar N.,“Optimizing the EDM Parameters to Improve the Surface Roughness of Titanium Alloy (Ti-6AL-4V)”, International Journal of Emerging Science and Engineering (IJESE) ISSN: 2319–6378, Volume-1, Issue-10, August 2013.
8) Chow H M., Yan B H., Huang F Y and Hung J C., “Study of added powder in kerosene for the micro-slit machining of titanium alloy using electro-discharge machining”, Journal of Materials Processing Technology 101 (2000),pp. 95-103.
9) Kansal H.K. , Singh S., Kumar P., “ Effect of Silicon Powder Mixed EDM on Machining Rate of AISI D2 Die Steel”, Journal of Manufacturing Processes Vol. 9,No , 1.(2007) ,pp.13-21.

10) Kumar S. and Batra U., "Surface modification of die steel materials by EDM method using tungsten powder-mixed dielectric." Journal of Manufacturing Processes 14 (2012) 35–40.
11) Syed K H. and Kuppan P. "Studies on Recast-layer in EDM using Aluminium Powder Mixed Distilled Water Dielectric Fluid", International Journal of Engineering and Technology (IJET) ISSN : 0975-4024, Vol. 5, No 2 Apr-May 2013.
12) Yilmaz O. and Okka M.A. "Effect of single and multi-channel electrodes application on EDM fast hole drilling performance", International Journal of Advance Manufacturing Technology 51 (2010) 185–194.
13) Gu L., Li L., Zhao W and Rajurkar K.P "Electrical discharge machining of Ti-6Al-4V with a bundled electrode" International Journal of Machine Tools & Manufacture 53 (2012) 100–106.
14) Hascalik A. and Caydas U., "Electrical discharge machining of titanium alloy (Ti–6Al–4V)",Applied Surface Science 253 (2007) 9007–9016.
15) Syed K H. and , Kuppan Palaniyandi K., "Performance of electrical discharge machining using aluminium powder suspended distilled water", Turkish J. Eng. Env. Sci. 36 (2012), pp.195 – 207.
16) Pandey A. and Singh S., "Current research trends in variants of Electrical Discharge Machining: A review", Vol. 2, No. 6, (2010), pp. 2172-2191.
17) Ojha K., Garg R K. and Singh K K., "MRR Improvement in Sinking Electrical Discharge Machining: A Review", Journal of Minerals & Materials Characterization and Engineering, Vol. 9, No.8, (2010) pp.709-739.
18) Garg R K., Singh K K., Sachdeva A., Sharma V S., Ojha K. and Singh S., "Review of research work in sinking EDM and WEDM on metal matrix composite materials" International Journal of Advance Manuf Technology 50 (2010), pp.611–624.
19) Kolli M. and Adepu k., "Influence of Span 20 Surfactant and Graphite Powder Added in Dielectric Fluid on EDM of Titanium Alloy" Bonfring International Journal of Industrial Engineering and Management Science Vol. 4, No.2, (2014), pp.62–67.
20) Kumar A., Maheshwari S., Sharma C. Beri N., "Realizing Potential of Graphite Powder in Enhancing Machining Rate in AEDM of Nickel Based Super Alloy

718" AMAE Int. J. on Production and Industrial Engineering, Vol. 01, No. 01, (2010), pp.48-51.

21) Takezawa H., Asano T. and Mohri N "Influence of Gap Phenomenon on Various Kinds of Powder-Suspended EDM" Int. J. of Automation Technology Vol.7,No.4, (2013), pp.419-425.

22) Parkash V. and Kumar D., "Effect of Powder Mixed Dielectric Medium on Tool Wear Rate in EDM" International Journal of Scientific Research Vol. 2, No. 2, (2013), pp.107-109.

23) Kumanan G., Kanagarajan D. and Karthikeyan R., " Modelling of Material Removal and Surface Roughness on Machining of Ti-6Al-4V Through EDM Process" International Journal of Mechanical & Mechatronics Engineering, Vol.14, No.1,(2014), pp.46-54.

24) Kaldhone S Y., Kavade M V. and Rawat U., "Effect of Powder Mixed Dielectric on Performance Measures of EDM for Tungsten Carbide" International Journal of Innovative Research in Advanced Engineering, Vol. 1, No.10 (2014), pp.106-111.

25) Laad M., Jatti V K S. and Jadhav P P., "Investigation into application of electrical discharge machining as a surface treatment process" Wseas transactions on applied and theoretical mechanics, Vol. 9, (2014), pp.245-251.

26) Nikalje A N. and Hambire U V., "Analysis of the influence of EDM parameters on surface Quality, MRR, EWR and Micro Hardness of AISI O2" International Journal of Scientific & Engineering Research, Vol. 5, No. 3, (2014), pp. 850-857.

27) Khedkar N K., Singh T P. and Jatti V K S., "Material migration and surface improvement of OHNS die steel material by EDM method using tungsten powder-mixed dielectric" Wseas Transactions on Applied and Theoretical Mechanics, Vol. 9, (2014), pp.161-166.

28) Janmanee P., Jamkamon K. and Kanchanasangtong T., "A study of surface hardness affecting in electrical discharge machining on AISI P20 plastic mould steel" Advanced Materials Research, Vols. 557-559 (2012), pp. 1791-1796.

29) Garg R K., Singh K K. and Ojha K., "Experimental Investigation and Modeling of PMEDM Process with Chromium Powder Suspended Dielectric" International Journal of Applied Science and Engineering, Vol. 9, No.2, (2010), pp.65–81.

30) Garg R K., Singh K K. and Ojha K., "Parametric Optimization of PMEDM Process using Chromium Powder Mixed Dielectric and Triangular Shape

Electrodes" Journal of Minerals & Materials Characterization & Engineering, Vol. 10, No.11, (2011), pp.1087–1102.

31) Reddy G B. and Vamsi V.S.P., "Parametric Analysis on Powder Mixed Electric Discharge Machining Of Various Steels Using Taguchi Method" International Journal of Advance Research in Science and Engineering, Vol. No.4, No.2, (2015), pp. 422-430.

32) Reddy G B., Kumar G N. and Chandrashekar K., "Experimental Investigation on Process Performance of Powder Mixed Electric Discharge Machining of AISI D3 steel and EN-31 steel" International Journal of Current Engineering and Technology, Vol.4, No.3, (2014), pp. 1218-1222.

33) Muniu J M., Ikua B W., Nyaanga D M.AND Gicharu S N., "Study on Effects of Powder-Mixed Dielectric Fluids on Electrical Discharge Machining Processes "International Journal of Engineering Research & Technology, Vol. 2, No.10, (2013), pp. 2449-2456.

34) Ramu B., Ganesh V. and Srinivasulu K., "Experimental Investigations on Powder Mixed Electric Discharge Machining" International Journal of Engineering Research & Technology, Vol. 3, No. 3, (2014), pp. 102-113.

35) Yu Z B., Jun T. and Masanori K., "Dry electrical discharge machining of cemented carbide" Journal of Materials Processing Technology Vol. 149,(2004), pp.353–357.

36) Lee,S.H.; Li,X.P.(2001):Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide, Journal of materials processing Technology, 115, pp.344-358.

37) Chow, H.M.; Yan, B.H.; Huang, F.Y. (1999): Micro slit machining using electro-discharge machining with a modified rotary disk electrode (RDE), Journal of Materials Processing Technology, 91, pp. 161–166.

Book References

38) Ghosh A. and Mallik a k., "Manufacturing Science", East-West Press Private Limited, New Delhi ,1998.

39) El-Hofy H., "Nontraditional and Hybrid Machining Processes", McGraw-Hill Private Limited, United States of America, 2005.

40) Marinov V., “Manufacturing Technology Non-traditional Processes” Chapman and Hall Private Limited. London, New York, 1974.
41) Tlusty G.,“ Manufacturing Processes and Equipment” , Prentice-Hall Private Limited , Upper Saddle River, 1999.
42) Pandey P C. and Shan H S., “Modern Machining Processes”, Tata McGraw-Hill Private Limited, New Delhi,2012.

Web References

43) http://www.productdesignfunda.com/technology/function-and-selections-of-dielectric-fluid-for-electric-discharge-machining-edm
44) http://www.nptel.ac.in
45) http://www.badgermetal.com/ml-edm-counter.htm

Conference References

46) Ganguly S., “A Detailed Review Of The Current Research Trends In Electrical Discharge Machining (Edm)”, Proceedings of the National Conference on Trends and Advances in Mechanical Engineering, YMCA University of Science & Technology, Faridabad, Haryana, Oct 19-20, 2012.
47) Agrawal A., Dubey A K. and Shrivastava P K., “Modeling and Optimization of Tool Wear Rate in Powder Mixed EDM of MMC” 2nd International Conference on Mechanical and Robotics Engineering (ICMRE 2013), Pattaya, Thailand, Dec. 17-18, 2013.
48) Ndaiman M B.,Khan A A. and Ali M Y., “Influence of Electrical Discharge Machaining process parameters on surface micro-hardness of Titanium alloy” Proceeding of the institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,(2013), pp.460-464.

Appendixs

Appendix A

Technical Data of EDM

1. Specification of Stabilizer	
Type	L
Supply Voltage Range (V)	320-470 V, 3 Phase , 50 Hz.
Output voltage (V)	415
Mains voltage tolerance (%)	±10
Correction rate (V/s)	30
Output Regulation (%)	±1
Frequency Range (Hz)	48-52
Connected Load (KVA)	10
Trip Time Delay (s)	4-5
Power consumption (KVA)	Approx. 7.5
Power Factor	Approx. 0.9 lag
2. **Working Parameters**	
Machine current maximum (A)	50
Open gap output voltage (V)	100
Input main voltage (V)	415 V, 3 Phase, 50 Hz
Rotary switch Peak Current Range (A)	0 to 70
Pulse-On Time (μs)	1 to 2000
Duty factor (%)	10 to 120
Pulse frequency (KHz)	0.22 to 330
Height (mm)	1325
Width (mm)	725
Depth (mm)	450
Weight (Kg)	300

Appendix B

List of controls

S.No.	List of Controls
1	Voltameter
2	Ammeter
3	R Phase Indication
4	Y Phase Indication
5	B phase indication
6	Low level indication
7	Over temperature indication
8	Over flow indication
9	Motor overload indication
10	Present depth indication
11	Fan failure indication
12	Reverse servo switch
13	Pump indication
14	Auto positioning indication
15	Spark on indication
16	Stop indication
17	Sparking time potentiometer
18	Lifting time potentiometer
19	Auto flushing function potentiometer
20	Impulse / force flushing function key
21	Buzzer selection key
2	Job set function key
23	Alarm reset function key
24	Fine current rotary switch
25	Coarse current rotary switch
26	Pre-ignition rotary switch
27	Gap control potentiometer
28	Pulse on time rotary switch
29	Duty cycle rotary switch

S.No.	List of Controls
30	Anti arc sensitivity potentiometer
31	Anti arc indication
32	Serve sensitivity potentiometer
33	Pre-ignition pulse indicator
34	Time totalizer
35	Emergency (Power) off push button
36	Home function key
37	Pre-set function key
38	Radial / diametral function key
39	MM / /Inch function key
40	ABS / Inc function key
41	Zero function key
42	Inch function indicator
43	MM function indicator
44	Diametral function indicator
45	Incremental function indicator
46	Absolute function indicator
47	Home function selection indicator
48	Position indicating display