THESIS

On

"Effect of powder mixed dielectric on Material removal rate, Tool wear rate and Surface properties in Electric Discharge Machining"

Submitted in the partial fulfillment of requirement for the award of the degree of

Master of Engineering

In

CAD/CAM & Robotics

Submitted by

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Certificate

I hereby certify that the work which is being presented in the thesis entitled, **"Effect of powder mixed dielectric on Material removal rate, Tool wear rate and Surface properties in Electric Discharge Machining"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in CAD/CAM & Robotics submitted in Mechanical Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of *Dr. T. P. Singh*, Professor, MED and *Dr. Ajay Batish*, Associate Professor, MED and refers other researcher's works which are duly listed in the reference section.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

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

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Abstract

In the process technology, as there are numerous advances at rapid rate, a large number of new materials are being developed everyday. These materials have the combination of properties, like light weight, corrosive resistance, high strength etc., which is not easy to obtain in general. The important aspect is that they satisfy the demands of today's industry, but the major problem is that it is very difficult to machine the newly developed materials. So, in order to manipulate them, newer machining methods have been developed. These methods are more efficient than the conventional ones. Electric discharge machining (EDM) is one of the most widely used methods among the new techniques. The main reason behind the popularity of the EDM is that its capability of machining the hard to machine materials and intricate shapes. EDM has been employed to effect/change the surface properties such as roughness and hardness of the die steels by varying the electrode material and by adding the various powders in the dielectric.

In this thesis work the literature available in the area of Surface modification by PMEDM (Powder Mixed EDM), EDM in general and effect of PMEDM on Tool Wear Rate and Material Removal Rate has been reviewed. Experiments were designed using Taguchi method so that effect of all the parameters could be studied with minimum possible number of experiments. Using Taguchi method, Appropriate Orthogonal Array has been chosen and experiments have been performed as per the set of experiments designed in the orthogonal array. Signal to Noise ratios are also calculated to analyze the effect of PMEDM more accurately.

From the point of view of industrial applications, die steel is a very important material and that's why for the purpose of experimentation EN31 die steel with copper electrode and kerosene as dielectric has been used. Graphite and copper powders were suspended in the dielectric kerosene. The effect of the powder mixed dielectric was studied by selecting peak current, Pulse on-time, Pulse off-time and Dielectric as factors and MRR, TWR, Micro-hardness and Surface roughness as responses. Three levels of each of the factors were taken and experiments were designed by Taguchi methodology. L27 Orthogonal Array was used and experiments were performed as designed by Taguchi method. Results of the experimentation were analyzed analytically as well as graphically using ANOVA and main effect-interaction plots, respectively. ANOVA has determined the percentage contribution of all factors upon each response individually. From the experimental results it is clear that the powders had changed the surface properties like surface roughness, micro hardness and improves the material removal rate and tool wear rate. Responses like 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.

Keywords: EDM, Taguchi design, PMEDM, Orthogonal Array.

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CHAPTER-1
INTRODUCTION

Traditional machining processes work on the principle that the tool is harder than the work-piece. Some materials, however, are too hard or too brittle to be machined by conventional methods. The use of very hard nickel-based and titanium alloys by the aircraft engine industry, for example, has stimulated non conventional machining methods. By conventional methods their machining is not only costly but also results into poor surface finish and shorter tool life. To overcome these difficulties, a number of *Newer Machining Methods* have been developed. These methods are not conventional in the sense that material removal does not occur due to plastic deformation and with the formation of chips.

These methods have found successful applications in several important industries for machining of components having complicated shapes made of hard materials like tungsten carbides, super-alloys, ceramics, refractory materials etc.

Newer machining methods can be classified on the basis of the type of energy they employ for purpose of metal removal. Broadly speaking they can be classified as below:

1. Mechanical Metal Removal Processes.
2. Electro-chemical Metal Removal Processes.
3. Thermal Metal Removal Processes.

Mechanical methods are characterized by the fact that material removal is due to the application of mechanical energy in the form of high frequency vibrations or kinetic energy of an abrasive jet. Practica1 machining methods that employ mechanical energy are:

I. **Ultra - Sonic Machining (USM):** In USM, material is removed from a workpiece with particles of abrasive that vibrate at high frequency in a water slurry circulating through a narrow gap between a vibrating tool and the workpiece. The tool, shaped like the cavity to be produced, oscillates at an amplitude of about 0.0005 to 0.0025 inch (0.013 to 0.062 millimetre) at 19,000 to

40,000 hertz (cycles per second).

II. **Abrasive Jet Machining (AJM):**

III. Water Jet Machining (WJM).

Electro-chemical methods are based on Electro-chemical dissolution of materials by an electrolyte under the influence of an externally applied electric potential. The practical methods that utilize this principle are:

I. **Electro-Chemical Machining (ECM):** ECM resembles electroplating in reverse. In this process metal is dissolved from a workpiece with direct current at a controlled rate in an electrolytic cell. The workpiece serves as the anode and is separated by a gap of 0.001 to 0.030 inch (0.025 to 0.75 millimetre) from the tool, which serves as the cathode. The electrolyte is usually an aqueous salt solution

II. Electro-Chemical Grinding (ECG).

In thermal methods, the material is removed due to controlled, localized heating of the work piece. This results into material removal by melting and evaporation. The source of heat generation in such cases can be widely different. Practical machining methods based on this principle are:

a. **Plasma Arc Machining (PAM):** PAM is a method of cutting metal with a plasma-arc, or tungsten inert-gas-arc, torch. The torch produces a high-velocity jet of high-temperature ionized gas (plasma) that cuts by melting and displacing material from the workpiece. Temperatures obtainable in the plasma zone range from 20,000° to 50,000° F (11,000° to 28,000° C). The process may be used for cutting most metals, including those that cannot be machined easily other wise.

b. **Electron Beam Machining (EBM):** The EBM technique is used for cutting fine holes and slots in any material. In a vacuum chamber, a beam of high-velocity electrons is focused on a workpiece. The kinetic energy of the electrons, upon striking the workpiece, changes to heat, which vaporizes minute amounts of the material. The vacuum prevents the electrons from scattering, due to collisions with gas molecules.

c.Laser Beam Machining (LBM): LM is a method of cutting metal or refractory materials by melting and vaporizing the material with an intense beam of light from a laser. Drilling by laser, although costly in energy since material must be melted and vaporized to be removed, is used to cut small holes (0.005 to 0.05 inch [0.13 to 1.3 millimetres]) in materials that are too difficult to machine by traditional methods.

d.Ion Beam machining (IBM): In IBM a stream of charged atoms (ions) of an inert gas, such as argon, is accelerated in a vacuum by high energies and directed toward a solid workpiece. The beam removes atoms from the workpiece by transferring energy and momentum to atoms on the surface of the object.

e.Electric Discharge Machining (EDM)

1.2 Electric Discharge Machining

In 1770, the English scientist, Priestley, first detected the erosive effect of electrical discharges on metals. During research (to eliminate erosive effects on electrical contacts) the soviet scientists, Lazarenko and Lazarenko (1940), decided to exploit the destructive effect of an electrical discharge and developed a controlled method of metal machining. In 1943, they announced the construction of the first Spark Erosion machine. The spark generator used in 1943, known as the Lazarenko circuit, has been employed over many years in powder supplies for EDM machines and an improved version is being used in many current applications.

Working Principle of EDM Process: The basic principle in EDM is the conversion of electrical energy into thermal energy through a series of discrete electrical discharges occurring between the electrode and work piece immersed in the dielectric fluid. The insulating effect of the dielectric is important in avoiding electrolysis of the electrodes during the EDM process. Spark is initiated at the point of smallest inter-electrode gap by a high voltage, overcoming the dielectric breakdown strength of the small gap. At this stage, erosion of both the electrodes takes place. After each discharge, the capacitor is recharged from the DC source through a resistor and the spark that follows is transferred to the next narrowest gap. The cumulative effect of a succession of sparks spread over the entire work piece surface leads to its erosion to a shape which is approximately complementary to that of the tool.

The dielectric serves to concentrate the discharge energy into a channel of very small cross-sectional area. It also cools the two electrodes and flushes away the products of machining from the gap. The electric resistance of the dielectric influences discharge energy and time of spark initiation. As the work piece is spark-eroded, tool has to advance through the dielectric towards it. A servo system is employed to ensure that the electrode moves at a proper rate to maintain the right spark gap, and to retract the electrode, if short-circuiting occurs.

Spark energy is the product of peak current and pulse-on time and since these process variables can be readily adjusted; machining conditions can selected for particular effects needed. Although the process is very complex, when the electrode is separated from the work piece, potential in the open circuit voltage is usually about 100V. As the dielectric begins to ionize, current starts flowing and the potential drops to a level of about 35 volts. Most of the electrode wear occurs during the ionization time.

Although EDM machining technology is widely used in mechanical manufacturing, its low efficiency and poor surface quality have been the key problem restricting its development. Therefore it is of great importance to improve the machining efficiency and surface quality of EDM technology. The EDM process can be compared with the conventional cutting process, except that in this case, a suitably shaped tool electrode, with a precision controlled feed movement is employed in place of the short duration electric impulses. EDM has found ready applications in the machining of hard metals or alloys which can not be machined easily by conventional methods.

The Electric Discharge machining (EDM) has been widely used as a material removal process to produce parts, dies and molds for several decades. It is only recently that surface modification methods by EDM have been studied. Like other machining methods, EDM machining is also divided into two phases: Rough machining and Finish machining. The finish machining phase requires high surface quality, while rough machining phase requires high machining efficiency with a certain quality. Numerous research results show that Powder Mixed EDM (PM-EDM) machining can distinctly improve the surface roughness and surface quality in the finish machining phase and obtain nearly mirror surface effects, which have lead to the development and application of PMEDM machining in finish machining, yet no research work has been reported on the application of PMEDM rough machining for improvement of efficiency. As PMEDM works with powder mixed working fluid, PMEDM machining has different machining mechanisms and results, as compared to conventional EDM machining. Further research on PMEDM machining, mechanism and machining effects in rough machining will ensure efficiency with a certain surface quality and promote its application in EDM rough machining.

Electric Discharge Machining (EDM) is used particularly when geometrically complex shapes need to be incorporated into high-strength, electrically conductive materials. The requirements of high quality surface vary depending on the fields of application. Spark Erosion machines, generators and suitable subassemblies were further developed during the last few years. As a result, the eroded surface quality and material removal rates have increased. Nowadays, the average roughness of $Ra = 0.1 \mu m$ and a Rim zone thickness of about 1 μm can be achieved. The increasing requirements imposed on dies and moulds subject to high levels of stress, in particular, often necessitate special finish machining after the erosion process. Vast research work has been concerned with powder mixed EDM (PM-EDM). An improvement on the surface roughness and surface quality has been achieved with this process. By lowering the breakdown strength of the insulating dielectric fluid and increasing the discharge probability, powder additives can cause higher material removal rates (MRR).

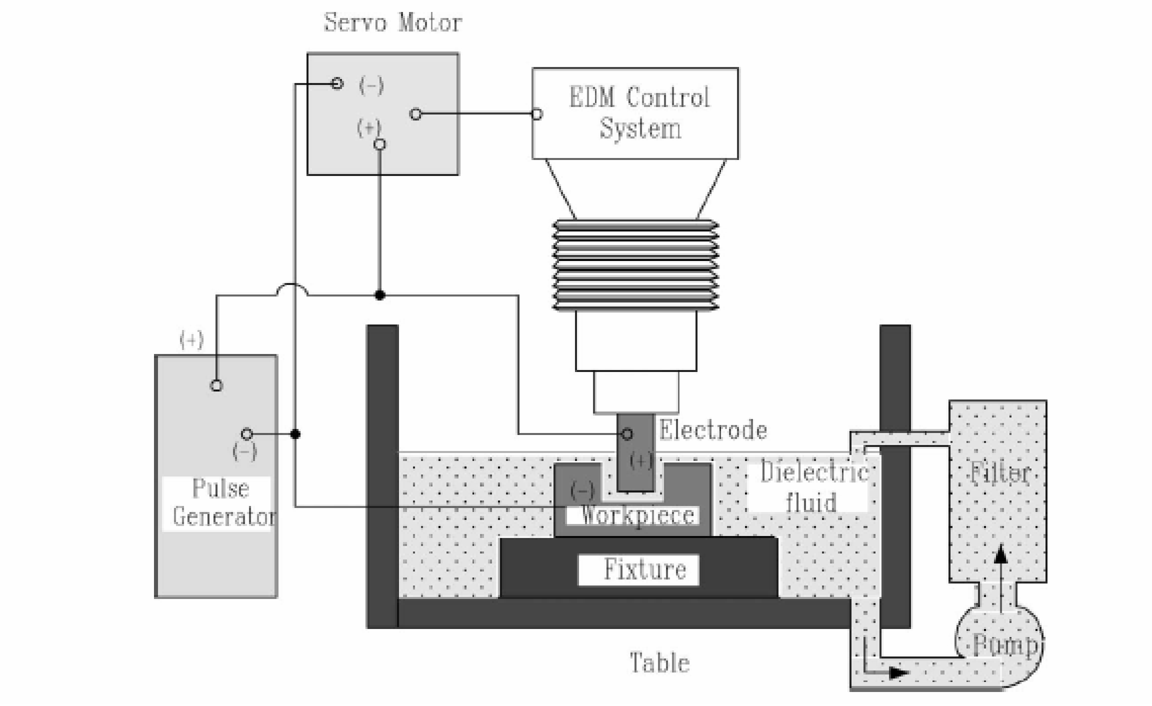


Figure 1.1 Typical set up for EDM.

1.3 Process Parameters

1.3.1 Discharge Voltage

Discharge voltage in the EDM is related to the spark gap and breakdown strength of the dielectric. Before current can flow, the open gap voltage increases until it creates an ionization path through the dielectric. Once the current starts to flow, 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 improves the flushing conditions and helps to stabilize the cut. MRR< TWR and surface roughness increases with increasing open circuit voltage because electric field strength increases.

1.3.2 Peak Current

This is the amount of power used in discharge machining, measured in units of amperage and is the most important machining parameter in EDM. During each on-time pulse, the current increases until it reaches a preset level, which is expressed as the peak current. Higher currents will improve MRR but at the cost of TWR and surface finish.

1.3.3 Pulse On-time & Off-time

Each cycle has an on-time and off-time that is expressed in units of microseconds. Since all the work is done during on-time, the duration of these pulses and the number of cycles per second are important. Metal removal is directly proportional to the amount of energy applied during the on-time. The energy is controlled by the peak current and the length of the pulse on-time. The resulting crater will be deeper and broader than a crater produced by a shorter on-time. Excessive on-times can be counter productive when the optimum on-time for each electrode-work material combination is exceeded, material rate starts to decrease.

The cycle is completed when sufficient off-time is allowed before the start of the next cycle. Off-time will affect the speed and stability of the cut. Shorter the off-time, the faster will be the machining operation. However, if the off-time is too short, the ejected work piece material will not be swept away by the flow of the dielectric and the fluid will not be deionized. This will cause the next spark to be unstable. Unstable conditions cause erratic cycling and retraction of the advancing servo. This slows down cutting more than long, stable off-times. Off-time must be greater than the deionization time to prevent continued sparking at one point.

1.3.4 Polarity

The polarity of the electrode can be either positive or negative. The current passing the gap creates high temperatures causing material evaporation at both electrode spots. As the electron processes show quicker reaction, the anode material is worn out predominantly. This causes minimum wear to the tool electrodes and becomes of importance under finishing operations with shorter on-times. However while longer discharges, the early electron process predominance changes to positron process, resulting in high tool wear. In this experiment setup, positive polarity is selected.

1.3.5 Electrode Gap

The tool servo-mechanism is of considerable importance in the efficient working of EDM and its function is to control responsively the working gap of the set value. Mostly electro-mechanical systems are used. The most important requirements for good performance are gap stability and the reaction speed of the system; the presence of the backlash is practically undesirable.

1.3.6 Type of dielectric Flushing

In this experiment, among all the flushing methods, normal flow flushing is used. In it, the dielectric fluid is fed to the inter-electrode gap from an opening in the tool. It results in the good flushing.

There are various parameters which are to be selected before the experiment is performed. As soon as suitable voltage is applied across the electrodes, the potential intensity of the electric field between them builds up, until at some predetermined value, at which the individual electrons break loose from the surface of the cathode. The voltage at which the electrons start to break loose from the surface of the cathode is known as breakdown voltage, it is usually 0.72 times the supply voltage. Now the increase in breakdown voltage will result in increase in energy per spark, this will lead to increase in MRR as shown in the Figure 1.3, Figure 1.4, Figure 1.5 and Figure 1.6.

The Figure 1.3 shows the effect of voltage and current on metal removal, here the dielectric used was kerosene, tool used was brass, work material used was low carbon steel and focus was on tool electrode area.

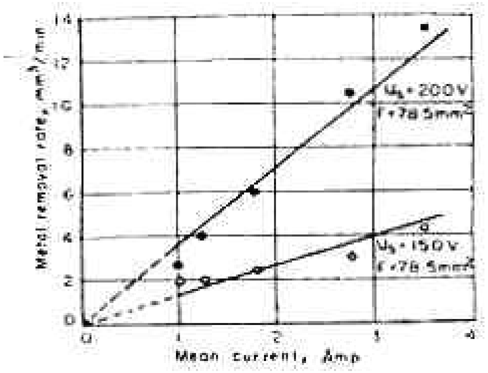


Figure 1.2 Effects of Breakdown Voltage and Mean Current on MRR

As shown in Figure 1.3 as the voltage was increased the MRR as well as the Mean Current also increase, rebuilding in higher MRR which may lead to cracks in the working surface and hence poor surface finish is obtained. Hence the machining should be done at a suitable voltage so that good surface finish should be obtained.

The Figure 1.4 shows the effect of current density on the removal rate of steel when machined by brass tool.

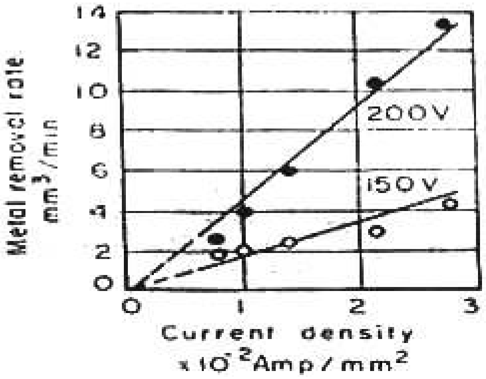


Figure 1.3 Effect of Current Density on MRR

It is seen that as the current density is increased the MRR tends to increase, so at higher current density MRR will be more which will lead to cracks in the working surface and hence poor surface finish is obtained. As the current density is the ratio of I/A (current/area) so the current should be supplied according to the area of the work piece so that good surface finish is obtained. Figure 1.5 shows the effect of machining area on the rate of metal removal. Work material used was low carbon steel, tool used was brass and the dielectric used was kerosene. In the beginning the machining area increases but after a point it starts to decrease. This is because of the reason that in the beginning the current density increases as current is more and the area is less but after some time of machining the machining area increases and the current remains the same which will lead to low current density hence poor surface finish. Hence an optimal balance should be obtained between current and machining area for good surface finish. The Figure 1.6 shows the effect of pulse energy on MRR. Work material used was low carbon steel, tool used was brass electrode and dielectric used was kerosene.

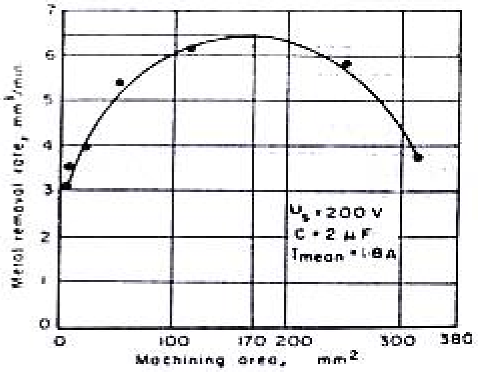


Figure 1.4 Effect of machining area on MRR

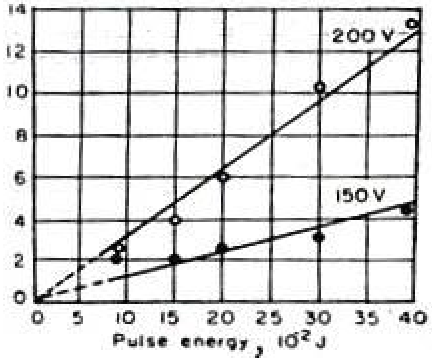


Figure 1.5 Effect of pulse energy on MRR

The pulse energy at a constant voltage is varied by changing the size of the capacitor used. It is shown by the figure that MRR increases with increase in pulse energy. Figure 1.7 shows that the cutting power depends upon the relative voltage to which the capacitor is charged. If the gap is larger than the optimum, the consequent reduction in frequency is not compensated for an increase in energy per spark and hence the power falls. At shorter gaps the power decreases because the increased frequency is not sufficient to compensate for the reduction in stored energy. This is because of the following reasons:

- The dielectric gets contaminated with metal particles and breakdown will occur at lower voltage.
- With increasing power, resistance is reduced. This helps in dielectric breakdown at lower voltages.

The EDM process changes not only the surface of the Workpiece metal, but also the subsurface. Three layers are created on the top of the unaffected Workpiece metal. The spattered EDM surface layer is created when expelled molten metal and small amounts of electrode materials form spheres and spatter the surface of the Workpiece. This spattered material can be easily removed. The next layer is the recast layer. The action of EDM has actually altered the metallurgical structure and characteristics in the recast layer. This layer is formed by the unexpelled molten metal solidifying in the crater. The molten metal is rapidly quenched by the dielectric. Micro-cracks can form in this very hard, brittle layer.

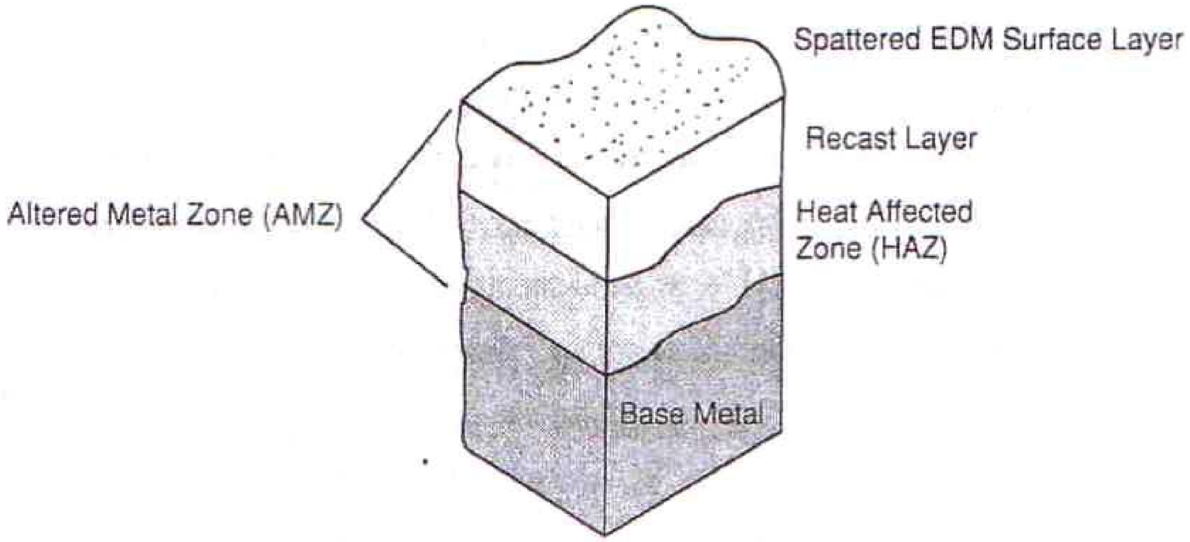


Fig 1.6 Layers of EDMed surface

The last layer is the Heat Affected Zone or Annealed layer, which has only been heated, not melted. The depth of the recast layer and the heat affected zone is determined by the heat sinking ability of the material and the power used for the cut. This altered metal zone influences the quality of the surface integrity.

1.4 Problem Identification

It is observed that although a lot of work has been done in the field of Electric Discharge Machining related to Material Removal Rate and Tool Wear Rate. But effect of PMEDM (Powder Mixed Electric Discharge Machining) on the various process parameters such as Material Removal Rate and Tool Wear Rate has not been studied yet. In past, work has been done using various powders such as nickel, Silicon, Titanium etc., but no one has tried yet Copper powder. Copper is a highly conductive material, so its interesting to study the effect of copper mixed dielectric upon the Material Removal Rate and Tool Wear Rate and the results are compared with that of Graphite powder. Further effect of PMEDM has also been studied upon Micro-Hardness and Surface Roughness of machined surface of the EN-31 die steel work-piece.

1.5 Outline of thesis work

The objective of this work is to study the effect of powder mixed dielectric upon the Material Removal Rate and Tool Wear Rate. For the purpose of experimentation, EN 31 die steel is used along with copper electrode. Kerosene has been used as dielectric. Reason for using kerosene as dielectric is that it is a good carrier of heat and has good flushing properties. The percentage of carbon in EN 31 die steel is 0.35%, which is very small as desired. Copper and graphite powders were added into the dielectric and their effect has been studied. Experiments were designed using Taguchi method so that effect of all the parameters has been studied with minimum possible number of experiments.

Using Taguchi method, Appropriate Orthogonal Array has been chosen and experiments have been performed as per the set of experiments designed in the orthogonal array. Signal to Noise ratio are also calculated to analyze the effect of PMEDM more accurately.

1.6 Organization of the Study

The thesis work has been divided into five chapters. Chapter 1 covers the need of non-conventional machining and basic introduction to the various non conventional machining methods. It also includes the basic working principle of the EDM process and the effect of various process parameters on Material Removal Rate, Tool Wear Rate, and Surface Roughness etc. along with the outline of the study and organization of the thesis. Chapter 2 contains latest literature review, recent developments in the EDM mainly in the field of PMEDM (Powder Mixed EDM). In chapter 3, design of study has been discussed in detail. Design of study includes the selection of Orthogonal Array, Signal to noise ratio and Introduction to Taguchi Method. Results of experimentation, in graphical as well as analytical form, have been presented and discussed in chapter 4. Chapter 5 consists of results, conclusion and limitations of present study and future scope of the work in detail.

CHAPTER-2

LITERATURE SURVEY

2.0 Introduction

This chapter gives an extensive review of literature upon 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.

2.1 EDM Process

EDM is an electro sparking method of metal working which involves an electric erosion effect. This electric erosion effect connects the breakdown of electrode material which accompanies any form of electric discharge. Researchers are actively engaged in experimentation related to EDM process. The areas of focus have been to select parameters for improving material removal rate (MRR), tool wear rate, use of additives for process improvement and surface quality work carried out by some researchers is briefly presented here. Many researchers have worked on the work pieces, using EDM machine, to see the effect of additives in dielectric fluid, changes in the re-solidified layer, etc. Given below is the work of some of the researchers.

Abbas et al, Solomon et al and Bahari et al [2006] have been studied the recent trends in the field of Electrical discharge machining (EDM) which is one of the earliest non-traditional machining processes. EDM process is based on thermoelectric energy between the work piece and an electrode. A pulse discharge occurs in a small gap between the work piece and the electrode and removes the unwanted material from the parent metal through melting and vaporizing. The electrode and the work piece must have electrical conductivity in order to generate the spark. There are various types of products which can be produced using EDM such as dies and moulds. Parts of aerospace, automotive industry and surgical components can be finished by EDM. They review the research trends in EDM on ultrasonic vibration, dry EDM machining, EDM with powder additives, EDM in water and modeling technique in predicting EDM performances.

The addition of powder particles to the electrical discharge machining (EDM) dielectric fluid modifies some process variables and creates the conditions to achieve a higher surface quality in large machined areas. They presents a new research work that aims to study the improvement in the polishing performance of conventional EDM when used with a powder-mixed-dielectric (PMDEDM). The analysis was carried out varying the silicon powder concentration and the flushing flow rate over a set of different processing areas and the effects in the final surface were evaluated. The evaluation was done by surface morphologic analysis and measured through some quality surface indicators. The results show the positive influence of the silicon powder in the reduction of crater dimensions, white-layer thickness and surface roughness. Moreover, it was demonstrated that an accurate control of the powder concentration and flushing flow is a requirement for achieving an improvement in the process polishing capability.

It is concluded from the study that the crater diameter, crater depth and the white-layer thickness are reduced by the use of silicon powder particles suspended in the dielectric.

Two parameters of the process were studied over several electrode areas:

- powder concentration
- flushing flow rate.

The quality was evaluated through the morphologic analysis of the surface and measurement of its roughness and craters and white-layer dimensions.

Ho and Newman [2003] have given the state of the art EDM. Powder mixed EDM (PMEDM) has a different methodology than from conventional EDM, which can improve the surface roughness. However, little research work has been carried out to study the PMEDM in rough machining. In this paper, experimental research on the machining efficiency and surface roughness of PMEDM in rough machining has been conducted. The results shows that PMEDM clearly improves the machining efficiency and at the same time surface roughness by selecting proper discharge parameters.

From the study it is concluded that

- PMEDM makes discharge breakdown easier, enlarges discharge gaps and passages and lastly forms evenly distributed and large and shadow shaped etched cavities. The machining efficiency of PMEDM is much better than conventional EDM.

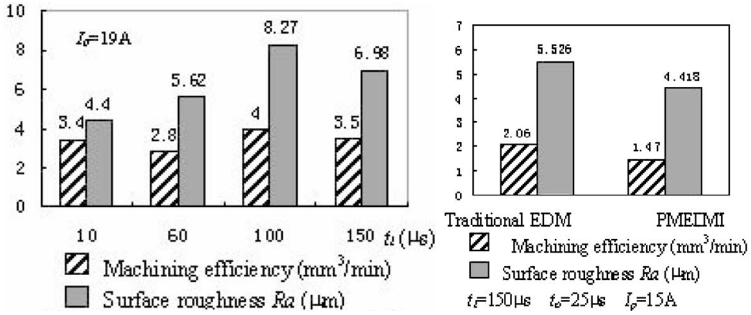


Figure 2.1 Comparisons of PMEDM and Conventional EDM

- The result for surface roughness is also same as that of machining efficiency. Because of much of loss of discharge energy in discharge gaps and reduction of ejecting force on the melted material, the surface roughness becomes smaller in PMEDM than that of conventional EDM.

Kansal, et al (2005), have carried out a study has been made to optimize the process parameters of Powder Mixed Electric Discharge Machining (PMEDM). Response surface methodology has been used to plan and analyze the experiments. Pulse on time, duty cycle, peak current and concentration of silicon powder added into the dielectric fluid of EDM was chosen as variables to study the process performance in terms of material removal rate and surface roughness. Experiments are performed on a newly designed experimental set up developed in the laboratory. The results identify the most important parameters to maximize material removal rate and minimize surface roughness. The recommended optical process conditions have been verified by conducting conformation experiments.

Summarizing the results of experiments the following conclusions can be drawn:

- The silicon powder suspended in the dielectric fluid of the EDM effects both MRR and SR. The slope of the curve indicates that the MRR increases with the increase in the concentration of the silicon powder. Therefore more improvement is expected at still higher concentration of silicon powder.
- More improvement in SR is expected at higher concentration of silicon powder.
- The combination of high peak current and high concentration yield more MRR and small SR.

- The conformation test shows that the error between experiment and predicted value of MRR and SR are with in ±8% and -7.85% to 3.15% respectively.

Keskin et al, Selc et al, Halkacı et al and Kizil et al [2005] have conducted experiments to study the effect of various machining parameters upon surface roughness in process which is a nontraditional production method that has been widely used in the production of dies throughout the world in recent years. The most important performance measure in EDM is the surface roughness; among other measures material removal and tool wear rates could be listed. Experiments were performed to determine parameters effecting surface roughness. The data obtained for performance measures have been analyzed using the design of experiments methods. A considerably profound equation is obtained for the surface roughness using power, pulse time, and spark time parameters.

From the experimental results obtained it is concluded that the results could become a reference to EDM manufacturers especially when the work-piece is steel and a copper electrode is used.

- It would be possible to manufacture parts with certain surface roughness requirements using the results instead of trial and error. Therefore, the manufacturing time will be decreased.
- Effects of machining parameters on the surface roughness values of machined components by EDM have been investigated experimentally.
- The surface roughness has an increasing trend with an increase in the discharge duration. This is mainly due to more discharge energy released during this time and expanding the discharge channel.
- A CNC electro discharge machine can be used for conventional machine tool. A two level designed experiment for further research.
- The MRR increases sharply with increase in current. In the present study, the highest MRR was obtained during machining of aluminum using a brass electrode.

Khan et al [2007] has presented in this study an analysis to evaluate the electrode wear along the cross-section of an electrode compared to the same along its length during EDM of aluminum and mild steel using copper and brass electrodes. In an overall performance comparison of copper and brass electrodes, it is found that electrode wear increases with an increase in both current and voltage, but wear along the cross-section of the electrode is more compared to the same along its length. This is due to easier heat transfer along the length compared to the same along the cross-section of the electrode. It was also found that the wear ratio increases with an increase in current. That means, though a higher current causes more removal of work material and the electrode, comparatively more material is removed from the electrode. The highest wear ratio was found during machining of steel using a brass electrode. The low thermal conductivity of brass electrodes causes less heat loss, and its low melting point results in fast melting of the electrode material. At the same time, low thermal conductivity of steel results in poor heat absorption, and its high melting temperature causes poor removal of work material. These factors result in the highest wear ratio during machining of steel using a brass electrode. The highest material removal rate was observed during machining of aluminum using brass electrodes. Comparatively low thermal conductivity of brass as an electrode material does not allow the absorption of much heat energy, and most of the heat is utilized in the removal of material from aluminum work-piece at a low melting point. But during machining of steel using copper electrodes, a comparatively smaller quantity of heat is absorbed by the work material due to its low thermal conductivity. As a result material removal rate becomes very low.

From the above discussions the following conclusions can be drawn:

1. Electrodes undergo more wear along their cross-section compared to that along its length.
2. EW increases with increase in current and voltage. Wear of copper electrodes is less than that of brass electrodes. This is due to the higher thermal conductivity and melting point of copper compared to those of brass.
3. During machining of mild steel, electrodes undergo more wear than during machining of aluminum. This is due to the fact that the thermal conductivity of aluminum is higher that of mild steel, which causes comparatively more heat energy to dissipate into the electrode during machining of mild steel
4. The WR increases with increase in current and gap voltage Vg. The highest wear ratio was found during machining of steel using a brass electrode.

Kumar and Singh [2007] have performed a comparative study of the performance of different electrode materials in two media. Electrical discharge machining (EDM) has been recognized as an efficient production method for precision machining of electrically conducting hardened materials. Copper and brass are two commonly used electrode materials with kerosene as the dielectric medium. Then comparison of the performance of copper -chromium alloy with copper and brass as EDM electrode materials for machining OHNS die steel using kerosene and distilled water as dielectric media has been made. Keeping all other machining parameters same, the hardened work material was machined with the three electrodes at different values of discharge current. It has been found that copper -chromium alloy shows better results than copper and brass in terms of material removal rate, dimensional accuracy (lateral over cut) and surface finish in both the dielectric media. At the same time, tool wear rate of this alloy is lower which results in better accuracy and trueness of the machined profiles because the mirror image of the tool electrode is reproduced in the work piece. Regarding the use of distilled water as a dielectric medium, though material removal rate is low and tool wear rate is high, but hardness and finish of the machined surface show a marked improvement.

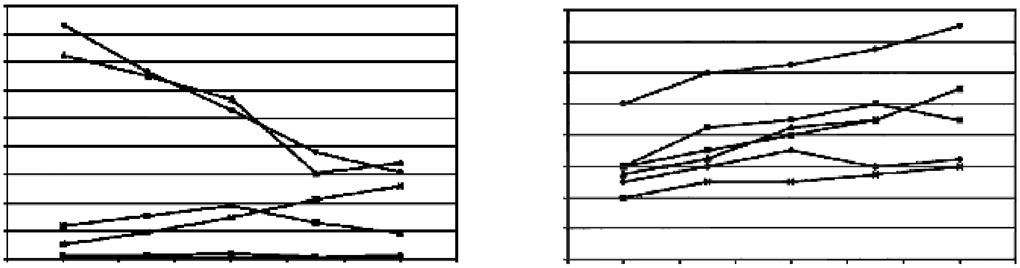


Figure 2.2 Variations of tool wear rate and dimensional accuracy with discharge current

Following outcomes can be drawn;

- Copper-chromium alloy clearly distinguishes itself as a superior electrode material which gives higher material removal rate, superior surface finish and least over cut (better dimensional accuracy) in both the dielectric media.
- The tool wear rate of this alloy is very low. It is especially important in EDM process because the machined surface is a mirror-image of the electrode shape and any unequal shape degeneration of the tool electrode may lead to the rejection of manufactured parts.

- Though copper-chromium alloy is expensive than copper and brass, the numerous advantages offered by it far outweigh the cost factor. MRR is less and TWR is higher in distilled water as compared to kerosene for all the three electrode materials.
- The addition of 1% chromium to copper has improved its properties as an EDM electrode material substantially. It is envisaged that there will be an optimum percentage of chromium in copper which will give the best overall performance
- It provides an opportunity to combine EDM with electrochemical machining by adding chemicals like sodium chloride or sodium nitrate in distilled water (which is not possible when kerosene is used as the dielectric), thus combining the advantages of both the processes. Other polar liquids like ethylene glycol may also be added to distilled water.

Work carried out by Lin and Lin [2001], to develop a new approach for the optimization of the electrical discharge machining (EDM) process with multiple performance characteristics based on the orthogonal array with the grey relational analysis has been studied. The grey relational grade obtained from the grey relational analysis is used to solve the EDM process with the multiple performance characteristics. Optimal machining parameters can then be determined by the grey relational grade as the performance index. The machining parameters, namely work-piece polarity, pulse on time, duty factor, open discharge voltage, discharge current, and dielectric fluid are optimized with considerations of multiple performance characteristics including material removal rate, surface roughness, and electrode wear ratio. From the experimental results it is clear that machining performance in the EDM process can be improved effectively by this approach.

It is concluded for the above study that the use of the orthogonal array with grey relational analysis has optimized the multiple performance characteristics of the EDM process. The outcomes of the study are;

- Grey relational analysis of the experimental results of electrode wear ratio, material removal rate and surface roughness can convert optimization of the multiple performance characteristics into optimization of a single performance characteristic called the grey relational grade. As a result, optimization of the complicated multiple performance characteristics can be greatly simplified through this approach.

- Performance characteristics of the EDM process such as material removal rate, surface roughness, and electrode wear ratio are improved together by using the method proposed by this study.

Miller et al, Shih et al and Qub et al [2003] have carried out experiments to study the effect of spark cycle upon Material removal rate. Electrical discharge machining (EDM) is a well-established machining option for manufacturing geometrically complex or hard material parts that are extremely difficult-to-machine by conventional machining processes. The non-contact machining technique has been continuously evolving from a mere tool and dies making process to a micro-scale application machining alternative attracting a significant amount of research interests. Despite a range of different approaches, this research shares the objectives of achieving more efficient metal removal coupled with a reduction in tool wear and improved surface quality. It reports on the EDM research relating to improving performance measures, optimizing the process variables, monitoring and control the sparking process, simplifying the electrode design and manufacture. It is concluded that

- The introduction of EDM to the metal cutting has been a viable machining option of producing highly complex parts, independent of the mechanical properties of Workpiece material. This is by virtue of the capability of EDM to economically machine parts, which are difficult to be carried out by conventional material removal processes.
- With continuous improvement in the metal removal efficiency and the incorporation of numerical control, the viability of the EDM process can be considerably extended.
- The basis of controlling the EDM process mostly relies on empirical methods largely due to the stochastic nature of the sparking phenomenon involving both electrical and non-electrical process parameters. The complicated interrelationship between the different optimized process parameters is therefore a major factor contributing to the overall machining efficiency. However, several means of improving the machining performance commonly measured in terms of MRR,

TWR and SR have been made with an overwhelming research interest being paid to the metallurgical properties of EDMed part.

A study carried out by Moro et al (2004), deals with the application technology of Electric Discharge Coating (EDC) to improve tool life by EDM instead of PVD or CVD. This thesis is an investigation of application technology and its possibilities to replace PVD or CVD. The main results are as follows

- The EDC tool will be limited to the application of low cutting speed conditions, such as drill.
- The worn amount of EDC coated drills is caused by friction coefficient. This high friction coefficient is lead by surface roughness.
- Application of a grinding machine is available under the high precision machining, in order to reduce the surface roughness.

From the study the following conclusions can be drawn:

- The tool treated by semi-sintered TiC electrode is improved in comparison with a TiN coating drill, but the improvement effect is not enough in the application of flat end mill tool.
- The phenomenon is caused by the difference of machining conditions between drills and flat end mills, and it should be considered as the cutting force, which acts as on tool edges during cutting and is non-continuously affecting cutting conditions.
- The tool treated by semi-sintered TiC electrode effects its tool life in the cutting conditions, where the cutting speed is less then 200m/min and feed rate is less then 0.3 mm/rev.
- When the cutting speed becomes large compared to TiN coating tool, EDC tool life falls relatively. This reason is considered due to reducing friction proof characteristics depending on the cutting force when the cutting force acting on the tool edge is high.
- Above –mentioned phenomenon is caused by relatively high surface roughness on the tools surface by EDC, consequently grinding process to EDC surface is considered in order to improve the surface roughness. As a result, although the

good surface height accuracy was a little bit influenced by TiC layer hardness, its surface is obtained under practical range with 0.431μm.

Ozgedik and Cogun [2006] have performed experimental investigation of tool wear in EDM as the development of new; advanced engineering materials and the need for precise and flexible prototypes and low-volume production have made the wire electrical discharge machining (EDM) an important manufacturing process to meet such demands. The research investigates the effect of spark on-time duration and spark on-time ratio, two important EDM process parameters, on the material removal rate (MRR) and surface integrity of four types of advanced material: porous metal foams, metal bond diamond grinding wheels, sintered Nd-Fe-B magnets, and carbon–carbon bipolar plates. During the wire EDM, five types of constraints on the MRR due to short circuit, wire breakage, machine slide speed limit, and spark on-time upper and lower limits are identified. An envelope of feasible EDM process parameters is generated for each work-material. Applications of such a process envelope to select process parameters for maximum MRR and for machining of micro features are discussed. Results of Scanning Electron Microscopy (SEM) analysis of surface integrity are presented.

From the study, the effects of spark cycle and pulse on-time on wire EDM of metal foams, metal bond grinding wheels, sintered Nd-Fe-B magnet, and carbon–carbon bipolar plate were investigated. An envelope of feasible EDM process parameters was generated for each work material. Results were mutually compared in this study. Regression analysis was applied to model the wire EDM MRR. SEM analysis was used to investigate effect of important EDM process parameters on surface finish. Although results presented are machine-dependent, this research provides the guidelines and procedures for the development of wire EDM process for machining new engineering materials to achieve different manufacturing objectives, either the high MRR, miniature features, or a compromise between the two. From this study the capability of wire EDM process to machine different advanced materials has been proved.

Advantages of non-traditional methods,

- Using traditional metal cutting methods, it is difficult to machine the metal foams without damaging the ligaments, is very difficult to machine to the precise shape.

- Sintered Nd-Fe-B magnet material is very brittle and easily chipped by using traditional machining methods. Carbon–carbon bipolar plate is delicate but can be machined easily by the EDM. The future research is to apply the envelope developed in this study for machining of miniature features and for high MRR EDM of advanced materials.

According to Pham, et al (2004), due to the high precision and good surface quality that it can give, EDM is potentially an important process for the fabrication of micro-tools, micro-components and parts with micro-features. However, a number of issues remain to be solved before micro-EDM can become a reliable process with repeatable results and its full capabilities as a micro-manufacturing technology can be realized. They worked on some resent developments in micro-EDM in its various forms and have discussed main research issues. They focus on the planning of the EDM process and the electrode wear problem. Special attention is paid to factors and procedures influencing the accuracy achievable, including positioning approaches during EDM and electrode grinding.

Summarizing the results of a series of experiments the following conclusions can be drawn:

- When assigning process tolerance for micro-EDM all aspects of the process, such as type of electrode grinding, type of positioning and duration of the operation, should be considered. All these activities will accumulate errors, which should be taken into account.
- The overall machining efficiency depends upon the complicated relationship between the different process parameters and there optimization is mainly based on empirical methods.
- To remain competitive as a micro-manufacturing technology, micro-EDM processes should use reliable algorithms and strategies with repeatable results. The proposed strategy for micro-milling replaces the complex calculations of other existing methods with simple length measurement.

Peças and Henriques [2007] have studied the variations of geometrical tool wear characteristics **edge and front wear** and machining performance outputs **Workpiece removal rate, tool wear rate, relative wear and Workpiece surface roughness** were investigated with varying machining parameters. Steel work pieces and round copper tools with a kerosene dielectric under different dielectric flushing conditions (injection, suction and static), discharge currents and pulse durations have been the parameters for the experiments. The experiments have shown that machining parameters and dielectric flushing conditions had a large effect on geometric tool wear characteristics and machining performance outputs.

In addition to injection and suction flushing methods, the static dielectric condition is also introduced to support the explanations about the experimental findings on the geometrical tool wear characteristics and machining performance outputs. It is found that,

- Increasing discharge current increases the Workpiece removal rate, tool wear rate, relative wear, front-surface wear rate and average surface roughness.
- The front-surface inclination angle, which is one of the important indications of geometrical tool wear, increases with discharge current and decreases slightly for high settings of current. Inner and outer edge-wear radii increase rapidly against increasing discharge current.
- The Workpiece removal rate increases with increasing pulse duration. The increase in tool wear rate with the increasing pulse duration is evident up to 50 μs. Further increase in pulse duration reduces the tool wear rate. The relative wear decreases with increasing pulse duration since the Workpiece removal rate increases at a faster rate than the tool wear rate.
- Workpiece average surface roughness increases with increasing pulse duration due to the larger craters formed on the surface. Increasing pulse duration leads to an increase in the tool front-surface wear rate and front surface inclination angle, and it leads to a decrease in the outer and inner edge-wear radii.
- The highest and the lowest Workpiece removal rates are obtained in suction flushing and the static condition, respectively. The low material removal rate in static condition is mainly due to improper flushing of the molten and evaporated Workpiece material from the machining gap. High tool wear rates are experienced in injection flushing. Suction flushing gives lower tool wear rates than injection flushing.

- The best surface quality is obtained in injection flushing. The high front-surface wears rates are observed in injection flushing whereas the low values are obtained in the static condition.
- The front surface inclination angle is always negative in injection flushing and it is always positive in suction flushing. Larger absolute inclination angles are obtained in injection flushing and smaller values are obtained in the static condition.
- The tool edge-wear geometry is modeled using circle arcs, exponential and polynomial functions. It is found that exponential model can be perfectly used to model the edge wear profiles.

Pecas and Henriques [2003] have found that Electrical discharge machining (EDM) is a technological process with a large industrial implementation. Its use is particularly intense when very complex shapes on hard materials with a high geometrical and dimensional accuracy are required. However, the technological capability of the process has limited its application when the specification of the part surface quality imposes polished and mirror-like characteristics. The addition of powder particles in suspension in the dielectric modifies some process variables and creates the conditions to achieve a high surface quality in large areas. They carried out the research work aiming to study the performance improvement of conventional EDM when used with a powder-mixed dielectric. A silicon powder was used and the improvement is assessed through quality surface indicators and process time measurements, over a set of different processing areas. The results show the positive influence of the silicon powder in the reduction of the operating time, required to achieve a specific surface quality, and in the decrease of the surface roughness, allowing the generation of mirror-like surfaces.

From the results of the experimental study following conclusions have been drawn;

- The use of silicon powder suspended on the dielectric under conventional EDM conditions enhances the polishing process performance. In particular, for 2 g/l silicon concentration, smooth and high reflective craters were achieved. The average surface roughness (*R*a) depends on the area and varies between0.09 μm

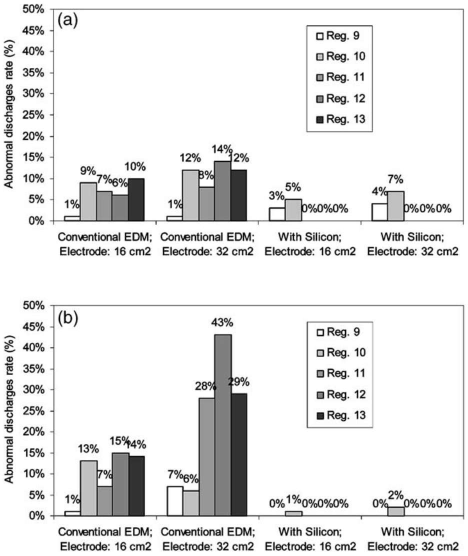


Figure 2.3 Frequency of abnormal discharges

for 1 cm2 and 0.57 μm for 64 cm2 electrode area. The surface roughness levels achieved are higher than the ones found in the literature. But one must notice that it was not used in any special system neither to eliminate capacitive effect nor to generate a specific pulse shape.

- When the silicon powder is used, the polishing time has a greater effect on decreasing the surface roughness. The presence of silicon in the dielectric almost eliminates the undesirable discharge conditions.
- Without silicon, the abnormal discharges remain present despite the longer processing time and limit the achievable final roughness.
- Research work can also be conducted in order to assess the ultimate surface roughness achievable with the increase of the polishing time.

Simao et al, Lee et al, Aspinwall et al, Dewes et al and Aspinwall et al [2002] have conducted experiments for surface modification using EDM. Electrical discharge machining (EDM) is a widely used process in the mould / die and aerospace industries. Details of operations are given involving powder metallurgy (PM) tool electrodes and the use of powders suspended in the dielectric fluid, typically aluminum, nickel, titanium, etc. Then experimental results are presented on the surface alloying of AISI H13 hot work tool steel during a die sink operation using partially sintered WC / Co electrodes operating in a hydrocarbon oil dielectric. An L8 fractional factorial Taguchi experiment was used to identify the effect of key operating factors on output measures (electrode wear, work piece surface hardness, etc.). With respect to micro hardness, the percentage contribution ratios (PCR) for peak current, electrode polarity and pulse on time were ~24, 20 and 19%, respectively. Typically, changes in surface metallurgy were measured up to a depth of ~30 μm (with a higher than normal voltage of ~270 V) and an increase in the surface hardness of the recast layer from ~620 HK0.025 up to ~1350 HK0.025.

Soni, et al (1996), presents Scanning Electron Microscopic (SEM) investigation on changes in chemical composition of resolidified layers of tool and the workpiece as well as the debris. An investigation has also been made on variation of micro-hardness, depth of resolidified layer and the Heat Affected Zone (HAZ) with pulse current and electrode rotation. This change in chemical composition occurs due to migration of material from either of the electrode during electro-discharge machining of high carbon high chromium die-steel (hardened) with rotating copper tungsten tool electrode. The rotation of electrode during machining also contributes towards these. The experiment was conducted by varying discharge currents and electrode rotation to study the effect of these parameters on alloying of tool and workpiece surface. An effort has also been made to compare these results with that of stationary electrode. It is found that appreciable amount migrates from the tool electrode to the workpiece and vice versa and got alloyed in the resolidified layer. The chemical composition of the debris also changes due to the pick up of elements from both the electrodes.

Summarizing the data given by a series of experiments the following conclusions can be drawn:

- An appreciable amount of material migrates from the tool electrodes to workpieces.
- An appreciable amount of material migrates from the workpieces to tool electrodes.
- The migration of tungsten from the tool electrode to the workpiece is more in built hole machining then through hole machining.
- The debris of die steel is alloyed with the tool electrode material.
- The surface hardness increases significantly.

Valentinčič and Junkar [2006] have done work for the detection of eroding surface in the EDM due to current gap. To achieve a high removal rate and low electrode wear in a sinking electrical discharge machining process (EDM), rough machining parameters have to be selected according to the size of the eroding surface. In general, the size of the eroding surface varies according to the depth of the machining. In this paper electric current signal in the gap depends on the size of the eroding surface. The significance of the process attributes of the electric current signal is established by inductive machine learning and the general decision rules are derived. The size of the eroding surface can be detected on-line by monitoring and evaluating the electric current signal in the gap.

From the study, following conclusions can be drawn:

- The electric current signal in the gap during the discharge depends on the surface power density in the gap
- At constant machining parameters, the size of the eroding surface determines the surface power density in the gap.
- Six attributes were defined on the electric current signal of the discharge and only when all of them were introduced to the modeler was the model able to classify the discharges into the classes which were defined according to the surface power density in the gap.

According to Wu, et al (2005), Electrical Discharge distribution effect can be achieved by the addition of the Aluminum (Al) powder in the dielectric. A fine surface roughness value of the work piece is thus obtained. However the electrostatic force among fine Al powder is found to agglomerate the Al powder in the dielectric. A surface can be adopted to separate the Al powder in the dielectric homogenously. Better surfaces even a mirror like quality of the machined work piece is thus desired. In the study, the effect of surfactant and Al powder added in the dielectric on the surface status of the work piece after the EDM is investigated.

It is observed that the best distribution effect is found when the concentrations of the Al powder and surfactant in the dielectric are 0.1 and 0.25 g/L, respectively. An optical surface roughness value of 0.172µm is achieved under the following parameters

- Positive polarity,
- Discharge current 0.3 A,

- Pulse duration time 1.5µs,
- Open circuit potential 140 V,
- Gap Voltage 90 V
- Surface concentration 0.25 g/L.

Thus the surface roughness status of the work piece has been improved up to 60% as compared to that EDMed under pure dielectric with high surface roughness Ra of 0.434µm.

Zhao et al, Meng et al and Wang et al [2002] have presented the application of research on PMEDM in rough machining. Electrical discharge machining (EDM) has been recognized as an efficient production method for precision machining of electrically conducting hardened materials. Copper and brass are two commonly used electrode materials in this process with kerosene as the dielectric medium. In this paper comparison in the performance of copper -chromium alloy with copper and brass as EDM electrode materials for machining OHNS die steel using kerosene and distilled water as dielectric media has been made. Keeping all other machining parameters same, the hardened work material was machined with three different types of electrodes one by one as pre the setup for different values of the discharge current. It has been found that copper -chromium alloy shows better results than copper and brass in terms of material removal rate, dimensional accuracy (lateral over cut) and surface finish in both the dielectric media. At the same time, tool wear rate of this alloy is lower which results in better accuracy and trueness of the machined profiles because the mirror image of the tool electrode is reproduced in the work-piece. Hence, it can be recommended as a good electrode material. Regarding the use of distilled water as a dielectric medium, though material removal rate is low and tool wear rate is high, but hardness and finish of the machined surface show a marked improvement.

It is concluded from this work that

- Copper-chromium alloy is better electrode material which gives higher material removal rate, superior surface finish and least over cut (better dimensional accuracy) in both the dielectric media. However, its impact on improving the hardness of the machined surface is only marginal and the tool wear rate of this alloy is very low.

- Though copper-chromium alloy is expensive than copper and brass, the numerous advantages offered by it far outweigh the cost factor's MRR is less and TWR is higher in distilled water as compared to kerosene for all the three electrode materials. But surface finish and hardness after machining show significant improvement, especially at higher values of discharge current.
- The effect of increasing percentages of chromium on these output parameters under similar machining conditions may be investigated. It is envisaged that there will be an optimum percentage of chromium in copper which will give the best overall performance.

From the review of literature it can be concluded that although a lot of work is being carried out on various aspects related to EDM yet there is a lot of scope for future work. The effect of PMEDM on the various parameters of EDM such as Material removal rate, Tool wear rate and also hardness and roughness etc. are to be worked upon. In the following chapters, the effect of PMEDM has been discussed in detail.

CHAPTER 3

DESIGN OF STUDY

A large number of input process parameters can be varied in the EDM process, each having its own impact on output parameters such as Material Removal Rate (MRR), Tool Wear Rate (TWR), and hardness of machined surface, surface finish, dimensional accuracy and overall surface integrity. Various input parameters are:

a. Discharge Voltage
b. Peak Current
c. Pulse Waveform
d. Pulse on-time
e. Pulse off-time
f. Pulse Frequency
g. Polarity
h. Electrode Gap
i. Type of Dielectric flushing

The effect of each of these parameters on EDM process is discussed in the literature review in detail. It is also known from the previous research works that out of the above listed parameters, four parameters directly affect the MRR and TWR in EDM. These four parameters are **peak current, pulse on-time, pulse off-time and polarity**. Out of these parameters, three parameters have been investigated thoroughly in this research work. One parameter **polarity** is kept fixed for the whole experiment. The range of first three parameters is decided by approach varying one parameter at a time. Polarity has been fixed as **straight polarity** (electrode negative) for all the experiments because it is desirable setting for material transfer to occur. With straight polarity, the energy available per discharge at work surface is higher as compared to the tool electrode and consequently material removal rate is also higher.

3.1 Experimental Design

As the objective of this research work is to study the effect of powder mixed in the dielectric upon MRR, TWR and Surface properties such as Surface roughness and micro hardness through material transfer from powder suspended in the dielectric medium by changing the various input machining process parameters, the design variables can be summarized as follows:

a) Two powders to be suspended in the dielectric one by one; namely graphite and copper.
b) Three levels of peak current to be used; because the non-linear behavior of process parameters can only be studied if more than two levels of a parameter are used.
c) Three levels of pulse on-time to be used.
d) Three levels of pulse off-time to be used.

For conducting the experiments, it has been decided to follow the Taguchi method of experimental design and an appropriate orthogonal array is to be selected after taking into consideration the above design variables. As the pattern of response of each other which can not be predicated at this stage, it has been decided not to include the work material as one of the variables of Taguchi orthogonal array. The effect of each suspended powder on the phenomenon of surface modification should be studied in order to correctly understand its behavior. Hence, it was decided to conduct experiments with each combination of work material, electrode and powder. Out of the above listed design variables, the orthogonal array was to be selected for four design variables(namely peak current, pulse on-time, pulse off-time and dielectric) which would constitute the orthogonal array.

The two most important output process parameters for dies and press tools are micro hardness and surface roughness of machine surfaces and the same have been selected as response parameters for this research work also. Micro hardness directly influences the life of the tool and surface roughness is significant from the point of view of lubrication retention and quality of the products made from these tools. The effect of the variation in input process parameter will be studied on these two response parameters and the experimental data will be analyzed as per Taguchi method to find out the optimum machining condition and percentage contribution of each factor.

The machining parameters that have been kept fixed throughout the experimentation are as follows:

Table 3.1 Fixed Input Process Parameters

S.No.	Machining Parameter	Fixed Value
1	Open Circuit Voltage	135 ± 5% Volts
2	Polarity	Straight
3	Machining Time	20min
4	Type of Di-electric	Kerosene
5	Electrode Quill Movement	10:4
6	Powder Concentration in Di-electric	15g/liter

3.1.1 Selection of Orthogonal Array & Parameter Assignment

In this experiment, there are four parameters at three levels each. The degree of freedom (DOF) of a three level parameter is 2 (number of levels-1), hence total DOF for the experiment is 8. There are three interactions (between current & Pulse on-time, current & pulse off-time and current and dielectric) which are to be studied in the experiment. Total DOF of the interactions is 12. The DOF of the orthogonal array selected should have higher than that of total DOF of the experiment. Total DOF for this experiment is 20. So the Orthogonal Array (OA) which is to be used is L27.

Table 3.1a DOF allocated to various factor combinations

Interaction	Units	DOF
Current (A)	Ampere	2
Pulse on-Time (B)	μ sec	2
Pulse off-time (C)	μ sec	2
Dielectric (D)	-	2
AXB	-	4
AXC	-	4
AXD	-	4
Total		20

Table 3.2 Standard L27 Orthogonal Array (Taguchi Design)

Exp. No.	Current	Pulse on-time	Pulse off-time	Dielectric
1	1	1	1	1
2	1	1	2	2
3	1	1	3	3
4	1	2	1	2
5	1	2	2	3
6	1	2	3	1
7	1	3	1	3
8	1	3	2	1
9	1	3	3	2
10	2	1	1	1
11	2	1	2	2
12	2	1	3	3
13	2	2	1	2
14	2	2	2	3
15	2	2	3	1
16	2	3	1	3
17	2	3	2	1
18	2	3	3	2
19	3	1	1	1
20	3	1	2	2
21	3	1	3	3
22	3	2	1	2
23	3	2	2	3
24	3	2	3	1
25	3	3	1	3
26	3	3	2	1
27	3	3	3	2

3.1.2 Signal-to-noise ratio for Response Characteristics

The parameters that influence the output can be categorized into two classes, namely controllable (or design) factors and uncontrollable (or noise) factors. Controllable factors are those factors whose values can be set and easily adjusted by the designer. Uncontrollable factors are the sources of variation often associated with operational environment. The best settings of control factors as they influence the output parameters are determined through experiments.

Controllable factors are divided into 3 main types:

- Those which affect the average levels of the response of interest, referred to as *Target Control Factors (TCF)*, sometimes called *signal factors.* In my thesis work they are Current (2, 4, 6 A), Pulse Duration (3, 4, 5), Polarity (Positive and Negative).

- Those which affect the variability in the response, the *Variability Control Factors (VCF)*. In my thesis work there is only one VCF factor that is Time which is taken constant (10 minutes).

Those which affect neither the mean response nor the variability, and can thus be adjusted to fit economic requirements, called the cost factors. In my thesis work a container is being prepared of 7.5 X 10.5 X 15.5 inches. It can hold up to 12 liters of kerosene which gave us an advantage over using 50 liters of kerosene. Now to save even more kerosene a metallic piece of 4 X 4.5 X 6 inches is kept in the container. Overall the kerosene, time like changing and adjusting, set up, stoppage; process engineer's time is being saved.

At the heart of Taguchi philosophy is the quality loss function. The loss function promotes efforts to continually reduce the variation in a product's functional characteristics. The change in quality characteristic of a product under investigation in response to a factor introduced in the experimental design is the 'signal' of the desired effect. The effect of the external factors (uncontrollable factors) on the outcome of quality characteristic is termed as 'noise'. The objective of any experiment is to achieve the best possible S/N ratio.

Finding a correct objective function to maximize in an engineering design problem is very important. Depending upon the type of response, the following three types of S/N ratios are employed in practice:

- **Higher the Better:**

$(S/N)_{HB}$ = -10 log (MSD_{HB})

Where $MSD_{HB} = \frac{1}{R}\sum_{j=1}^{R}\left(\frac{1}{{y_j}^2}\right)$

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

- **Lower the Better:**

$(S/N)_{LB}$ = -10 log (MSD_{LB})

Where $MSD_{LB} = \frac{1}{R}\sum_{j=1}^{R}\left({y_j}^2\right)$

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

- **Nominal the Best:**

$(S/N)_{NB}$ = -10 log (MSD_{NB})

Where $MSD_{NB} = \frac{1}{R}\sum_{j=1}^{R}\left(y_j - y_0\right)^2$

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

And, Y_j = Observed value of the response characteristic

Y_0 = nominal or target value of the results

R = 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 experimental work, the response characteristics have been studied as under:

1. Response Name : Micro-hardness
   Response type : Higher-the-better
   Units : HRC (Rockwell hardness number)
2. Response Name : Surface Roughness
   Response type : Lower-the-better
   Units : R_a value in microns
3. Response Name : Material removal rate
   Response type : Higher the better
4. Response Name : Tool wear rate
   Response type : Lower-the-better

3.2 ANOVA (ANalysis Of VAriance)

In statistics, analysis of variance (ANOVA) is a collection of statistical models, and their associated procedures, in which the observed variance is partitioned into components due to different explanatory variables. The initial techniques of the analysis of variance were developed by the statistician and geneticist R. A. Fisher in the 1920s and 1930s, and is sometimes known as Fisher's ANOVA or Fisher's analysis of variance, due to the use of Fisher's F-distribution as part of the test of statistical significance.

Following tables represents the data related to the experiments performed on the EDM and then testing performed on the Perthometer for Surface Roughness, Rockwell hardness testing machine for micro-hardness of the machined surface, MRR and TWR.

$$SS_i = \sum_{i=1}^{N} y_i^{\ 2} \quad - \frac{T^2}{N}$$

DOF = Levels of parameter -1

Variance = $\frac{SS_i}{DOF}$

F test = $\frac{Variationduetoparameter}{Variationduetoerror}$

$$e\_pooled = sumofSSduetoerrorandSSofallinsignificantfactors$$

$$SS^{'} = SSofsignificantfactor - \left(DOFofthatfactor \times \mathrm{var}iationduetoe\_pooled\right)$$

C% = $\frac{Ss^{'} \times 100}{TotalSS}$

If **F-critical > Ftest**

Only then the factor is significant for the given conditions.

In the ANOVA tables, several symbols have been used. Description of all those symbols is as given;

A1= Sum of all the value under columns having current value 2A.

A2= Sum of all the value under columns having current value 4A.

A3= Sum of all the value under columns having current value 6A.

B1=Sum of all the values under rows having pulse on-time value 3.

B2= Sum of all the values under rows having pulse on-time value 4.

B3= Sum of all the values under rows having pulse on-time value 5.

C1= Sum of all the values under rows having pulse off-time value 5.

C2= Sum of all the values under rows having pulse off-time value 6.

C3= Sum of all the values under rows having pulse off-time value 7.

D1= Sum of all the values under columns having dielectric with additive.

D2= Sum of all the values under columns having dielectric with copper as additive.

D3= Sum of all the values under columns having dielectric with graphite as additive.

T= sum of all the A’s or B’s or C’s or D’s.

S= Significant.

NS= Non-Significant.

3.3 Description of the EDM machine

The experiments have been conducted on Electric Discharge Machine model T-3822M of Victory Electromech (India) available at Thapar University, Patiala. A pictorial view of the machine is shown in Fig. 3.1.

Fig. 3.1 EDM used for the experimentation

Important technical data of the machine and list of controls have been summarized in **Appendix A** and **Appendix B** respectively. The x-axis and y-axis movements are given to the work table and the z-axis movement is on the tool holder. A servo-mechanism controls the downward movement of the tool holder during machining. Commercial grade kerosene is used as the dielectric medium. The dielectric tank has a capacity of 150 liters. A dielectric level indicator maintains the pre-set level (minimum 40 mm above sparking point) during machining and switches off the machine if it falls below the level due to any reason. Various process parameters such as pulse on-time, peak current, pulse off-time and ignition current etc. can be set from the control panel of the machine which is shown in the Fig. 3.2.

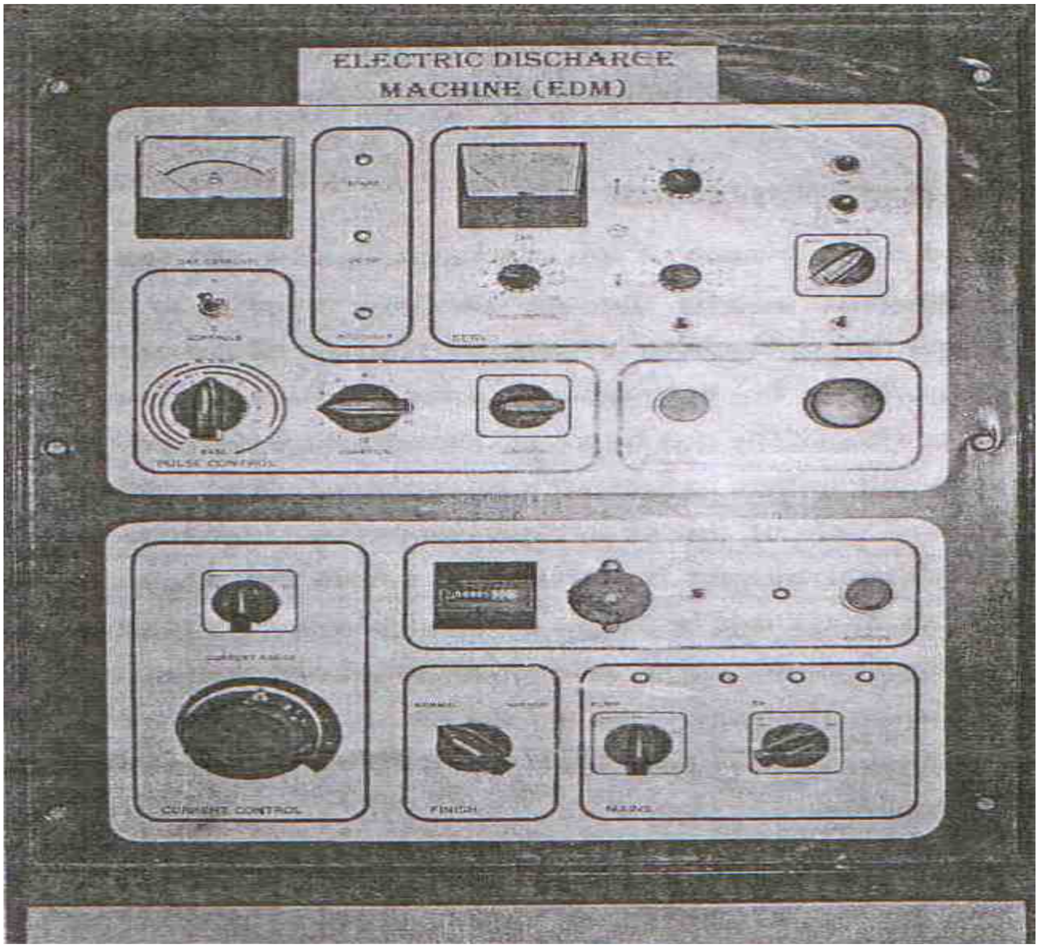


Fig. 3.2 Control Panel of the EDM

Pulse on-time and pulse off-time can be set with help of a rotary knob. Ignition can be set by a 4-position rotary switch which controls the energy of ignition of the discharge channel. This energy is maximum at position 1 and decreases progressively. Excessive ignition of the discharge channel provokes arcing tendency and instability of the machining process. The position of this switch has been kept fixed at position 3 for this experimentation. Machining current can be increased gradually by means of a knob and rotary switch. Both these switches should be at the minimum position when the sparking begins. A toggle switch 'SOFT PULSE' has been provided for the purpose of smoothening the discharge pulses which are very strong when average machining current is more than 2 to3 Amperes. Normal setting of this switch is position'1' and the same has been used in this experimentation.

3.4 Pilot experimentation

The values of the input process parameters for the EDM are as under:

Peak Current	:	2, 4, 6 Amperes
Pulse on-time	:	3, 4, 5 (knob positions)
Pulse off-time	:	5, 6, 7 (knob positions)

The values of the pulse off-time have been chosen towards the higher side with the aim of providing adequate cooling time to the recast material.

Table 3.3 Control Log for experimentation – L27 Orthogonal Array

Exp. No.	Current (Amperes)	Pulse on-time (knob reading)	Pulse Off-time (knob reading)	Dielectric
1	2	3	5	No
2	2	3	6	Cu
3	2	3	7	Gr
4	2	4	5	Cu
5	2	4	6	Gr
6	2	4	7	No
7	2	5	5	Gr
8	2	5	6	No
9	2	5	7	Cu
10	4	3	5	No
11	4	3	6	Cu
12	4	3	7	Gr
13	4	4	5	Cu
14	4	4	6	Gr
15	4	4	7	No
16	4	5	5	Gr
17	4	5	6	No
18	4	5	7	Cu
19	6	3	5	No
20	6	3	6	Cu
21	6	3	7	Gr
22	6	4	5	Cu
23	6	4	6	Gr
24	6	4	7	No
25	6	5	5	Gr
26	6	5	6	No
27	6	5	7	Cu

3.5 Experimental set up for powder mixed in the dielectric

For carrying out experimentation with powder-suspended dielectric, following points are to be kept in consideration:

- The powder should not enter into the main dielectric tank and the filtering unit.
- The dielectric should be continuously stirred to prevent settling of the powder.
- The machining should be done in small volume so that powder should not be wasted.
- Proper conductivity between the work piece and tool electrode must be maintained.

A pictorial view of the experimental set-up for the PMEDM is shown in the Fig. 3.3.

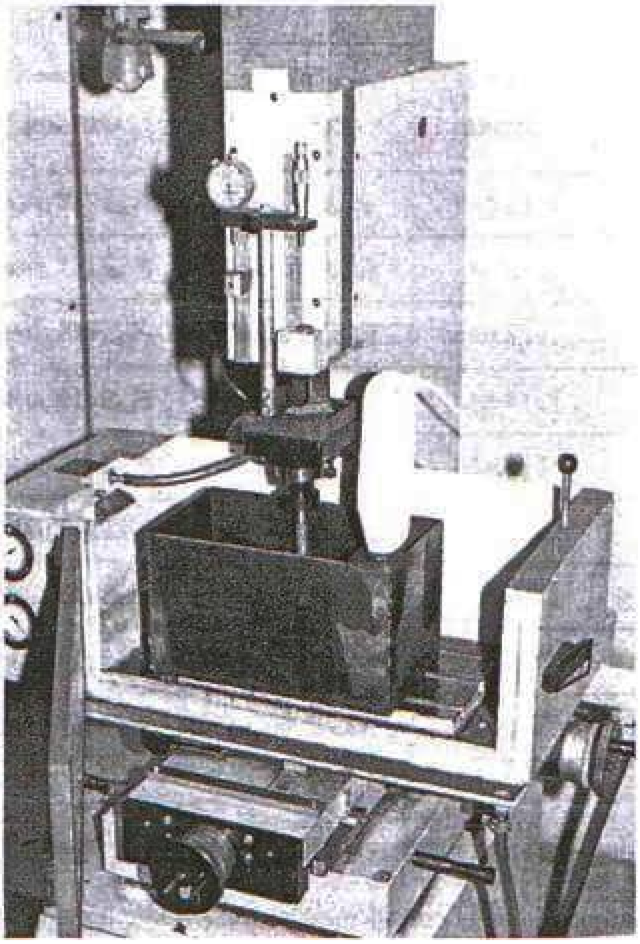


Fig. 3.3 Experimental set-up for machining with powder-mixed dielectric

The inside dimensions of the tank are 330 mm X 180 mm X 187 mm (length X breadth X height) and it has been fabricated out of mild steel sheet of thickness 1.6 mm. The critical dimension of the tank is its height as it is to be kept above the height of the main tank so that powder mixed dielectric does not enter into the main tank. A stirrer has been provided for keeping the powder in suspension. On the completion of the each cut, the powder mixed dielectric is siphoned off into a separate container by using a rubber tube. After changing the work piece and machine setting, the tank is filled with this powder mixed dielectric again.

3.6 Instruments used for analysis

Micro-hardness and surface roughness tests have been conducted on all the samples. The analysis of surface properties of selected samples has been then performed by such methods as observing the microstructure on scanning electron microscope (SEM), by X-ray diffraction and by chemical composition analysis on an optical emission spectrophotometer. The details for these instruments are as under;

(a) Micro-hardness tests have been done on micro hardness tester, HMV. In the Rockwell method of hardness testing, the depth of penetration of an indenter under certain arbitrary test conditions is determined. The indenter may either be a steel ball of some specified diameter or a spherical diamond-tipped cone of 120° angle and 0.2 mm tip radius, called Brale. The type of indenter and the test load determine the hardness scale (A, B, C, etc). In this case, diamond indentor is used.

(b) Surface roughness tests have been done on Perthometer, model M4P*i* of Mahr, Germany available at Thapar University, Patiala. The equipment uses the Stylus method of measurement, has a profile resolution of 12 nm and can measure a Value up to 100 μm. A tracing length of 1.5 mm was used for the experiment.

CHAPTER 4

ANALYSIS & DISCUSSION

This chapter includes the details of the experimental work performed on EDM machine along with the results of the experimental work. The objective of the experimentation is to study the effect of powder mixed dielectric upon the MRR, TWR, micro hardness and surface roughness mainly using die steel as the raw material. Also the effect has been studied on the Hardness and roughness of the machined surface. Signal to noise ratio was determined and graphs were generated on the basis of experimental data, analyzed and then SNR are determined. Three sets of experiments were conducted as under:

1. Experimental set up with no powder as additive.
2. Experimental set up with powder1 as additive.
3. Experimental set up with powder2 as additive.

4.0 Test results for work piece and powders

Before starting the experiment, the powders and work piece were tested. Following table shows the results

Table 4.1 Test results for composition of Work-piece and Powders

Material	**Copper powder**	**Graphite powder**	**EN-31 Work-piece**
Particle Size	325 mesh 25 μm	50 μm	C=0.35% P=0.04% Mn=0.4% Si=1% Cr=5% Mo=1.5% V=1% Fe= Balance
Percentage purity	99.5%	>99.5%	
Max. limit of impurities	Antimony (Sb) = 0.005% Arsenic (As) = 0.0002% Lead (Pb) = 0.05% Iron (Fe) = 0.005% Mangnese (Mn) = 0.005% Silver (Ag) = 0.005% Tin (Sn) = 0.005%	Maximum limit for impurities=0.2%	

After testing the work-piece and powders for their composition, experimentation has been performed. For the design of experiments, Taguchi methods have been used. Using Taguchi design, L27 Orthogonal Array has been selected (selection procedure has been described in the previous chapter) and experiments were performed according to the set of combinations of factors as given in L27 OA. Various factors for this study were Peak current, pulse on-time, pulse off-time and dielectric. For all these parameters, there were three levels of variation. For current, pulse on-time, pulse off-time and dielectric values at various levels are 2, 4 and 6 Amp; 3, 4 and 5 knob values; 5, 6 and 7 knob values and No, copper and graphite as additive. Work-piece was of EN-31 die steel and the electrode selected was of copper. Once all the parameters have been decided and level values were set, experimentation was performed. The results of experiments are given in Table 4.2. After the experimental results have been obtained, analysis of the results was carried out analytically as well as graphically. For graphical analysis of the experimental results plots, showing effects of all the factors upon responses, are generated in MINITAB. Then ANOVA of the experimental data has been done to calculate the contribution of each factor in each response. Various responses to be considered are MRR, TWR, Surface roughness and Micro-hardness. After studying the effect of all the factors on all the responses individually, Signal to noise ratio has been calculated for each response. For hardness and MRR, higher the best and for surface roughness, lower the better approach was used. Then after optimal condition have been calculated for hardness, surface roughness and MRR. The pictures of the specimen after performing the experiments are shown in the Figure 4.1.

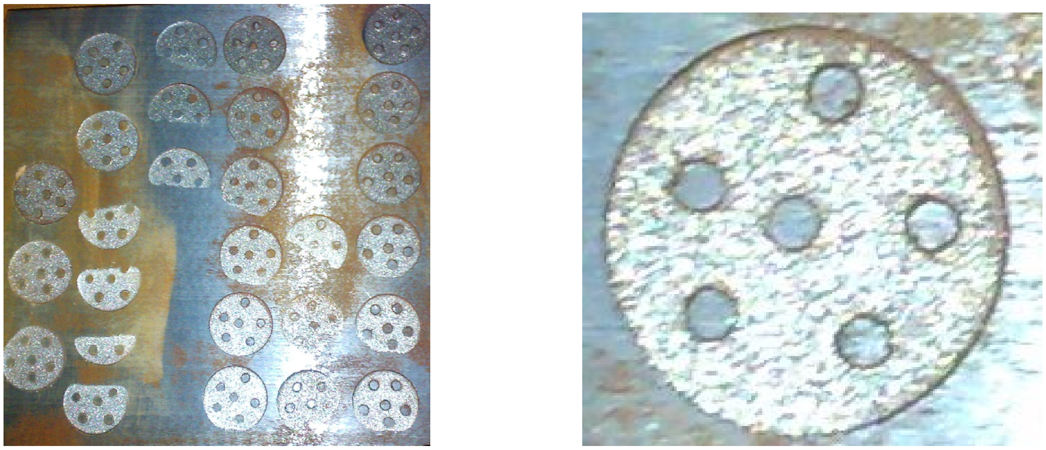


Figure 4.1 Specimen after machining at EDM

For calculating MRR and TWR, both work-piece and tool were taken to weighing machines, after unloading, and readings for their weight were noted. Following table gives all the response values at various values of responses:

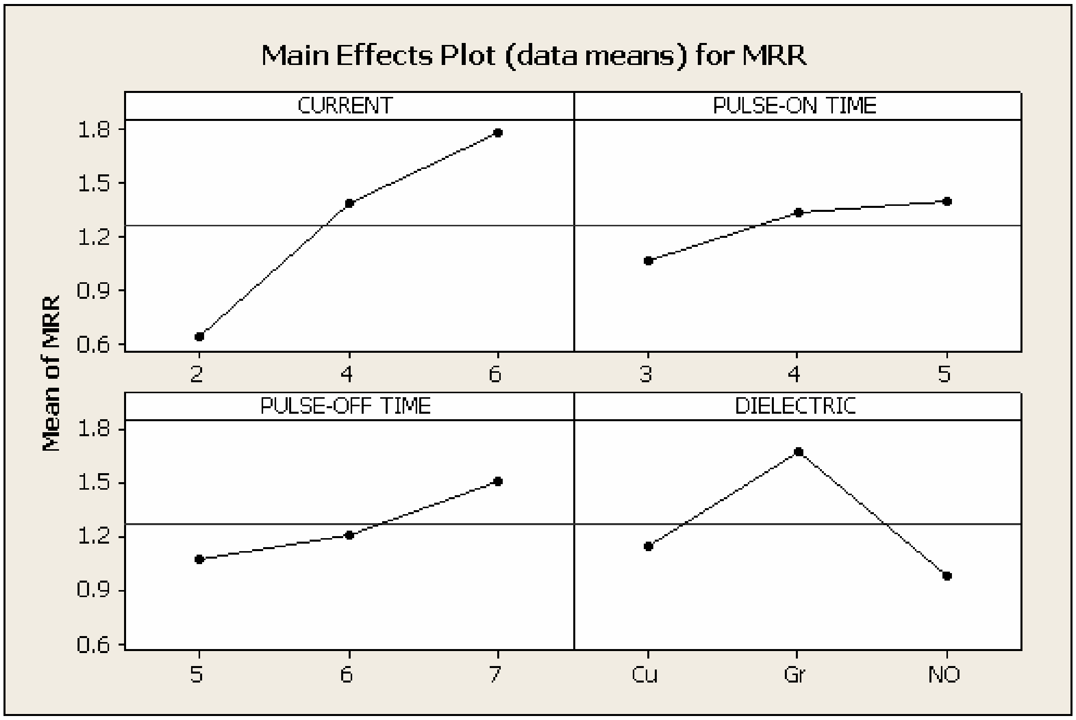
Table 4.2 Values of various responses

S.No.	Current	Pulse-on time	Pulse-off time	Dielectric	MRR (gms)	TWR (mg)	Surface roughness (microns)	Micro hardness (HRC)
1	2	3	5	NO	0.2	10	3.38	69
2	2	3	6	Cu	0.3	10	3.10	69.33
3	2	3	7	Gr	0.6	4	2.99	71.67
4	2	4	5	Cu	0.5	6	3.17	70
5	2	4	6	Gr	1	3	3.06	71.67
6	2	4	7	NO	1	10	3.68	69.33
7	2	5	5	Gr	0.5	2	3.22	72.33
8	2	5	6	NO	0.6	12	3.94	69
9	2	5	7	Cu	1	10	3.64	69
10	4	3	5	NO	0.5	13	3.72	69.33
11	4	3	6	Cu	1	20	3.34	70
12	4	3	7	Gr	2	18	3.18	73.67
13	4	4	5	Cu	1.5	20	3.63	71
14	4	4	6	Gr	1.5	17	3.40	73
15	4	4	7	NO	1.5	25	4.00	71
16	4	5	5	Gr	2	25	3.70	72.67
17	4	5	6	NO	1	35	4.30	71.33
18	4	5	7	Cu	1.5	30	3.98	72
19	6	3	5	NO	1	20	4.00	70
20	6	3	6	Cu	1.5	20	3.80	71
21	6	3	7	Gr	2.5	18	3.63	73.67
22	6	4	5	Cu	1	30	4.05	71.33
23	6	4	6	Gr	2.5	25	3.91	73.67
24	6	4	7	NO	1.5	40	4.42	72
25	6	5	5	Gr	2.5	20	4.08	73.33
26	6	5	6	NO	1.5	35	4.44	72
27	6	5	7	Cu	2	30	4.21	73.33

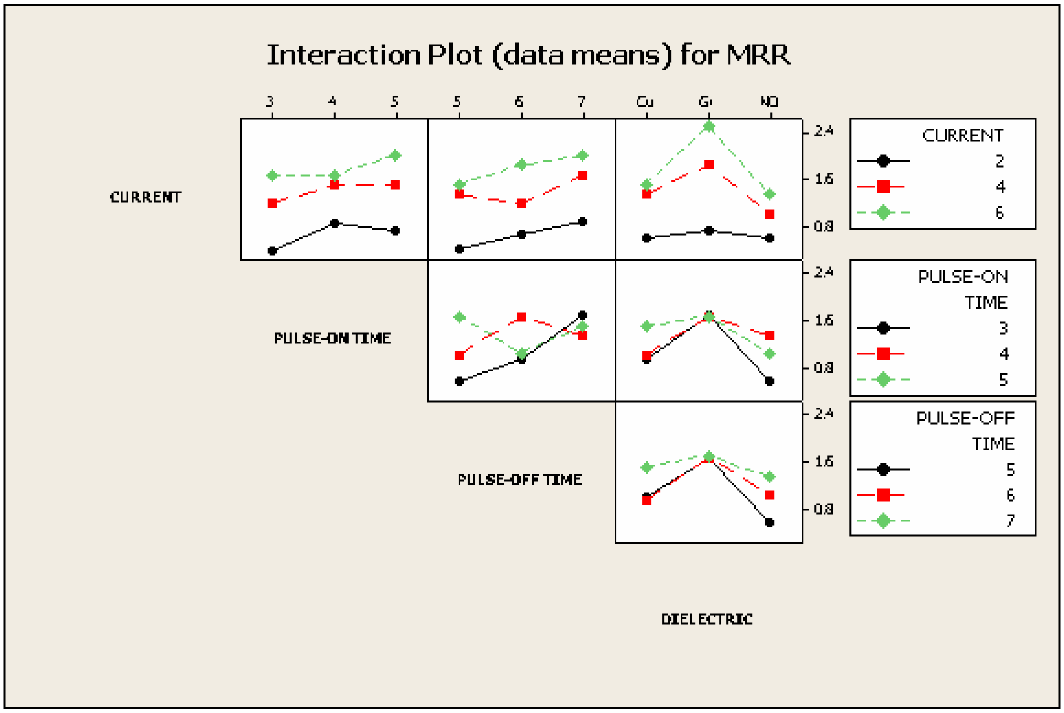
Table 4.2a SNR for MRR and TWR

S.No.	Current	Pulse-on time	Pulse-off time	Dielectric	MRR (gms)	SNR for MRR	TWR (mg)	SNR for TWR
1	2	3	5	NO	0.2	36.77698	10	-20
2	2	3	6	Cu	0.3	36.81842	10	-20
3	2	3	7	Gr	0.6	37.10675	4	-12.0412
4	2	4	5	Cu	0.5	36.90196	6	-15.563
5	2	4	6	Gr	1	37.10675	3	-9.54243
6	2	4	7	NO	1	36.81842	10	-20
7	2	5	5	Gr	0.5	37.18637	2	-6.0206
8	2	5	6	NO	0.6	36.77698	12	-21.5836
9	2	5	7	Cu	1	36.77698	10	-20
10	4	3	5	NO	0.5	36.81842	13	-22.2789
11	4	3	6	Cu	1	36.90196	20	-26.0206
12	4	3	7	Gr	2	37.34581	18	-25.1055
13	4	4	5	Cu	1.5	37.02517	20	-26.0206
14	4	4	6	Gr	1.5	37.26646	17	-24.609
15	4	4	7	NO	1.5	37.02517	25	-27.9588
16	4	5	5	Gr	2	37.2271	25	-27.9588
17	4	5	6	NO	1	37.06544	35	-30.8814
18	4	5	7	Cu	1.5	37.14665	30	-29.5424
19	6	3	5	NO	1	36.90196	20	-26.0206
20	6	3	6	Cu	1.5	37.02517	20	-26.0206
21	6	3	7	Gr	2.5	37.34581	18	-25.1055
22	6	4	5	Cu	1	37.06544	30	-29.5424
23	6	4	6	Gr	2.5	37.34581	25	-27.9588
24	6	4	7	NO	1.5	37.14665	40	-32.0412
25	6	5	5	Gr	2.5	37.30563	20	-26.0206
26	6	5	6	NO	1.5	37.14665	35	-30.8814
27	6	5	7	Cu	2	37.30563	30	-29.5424

4.1 Experimental results for MRR



Graph 4.1 Effect of various factors on the MRR



Graph 4.2 Interaction plot for MRR

In the Graph 4.1, effect of various factors i.e. current, pulse on-time, pulse off-time and Dielectric is shown on the Material removal rate. It is clear from the graphs that as the current increases, MRR goes on increasing. Same is the effect of pulse on-time and pulse off-time, but the rate of increase is comparatively lower than that of current, whereas in case of dielectric powder suspended kerosene gives better results than that of simple kerosene and the graphite suspended kerosene gives higher material removal rate than copper one. Reason for the better results with powder mixed dielectric is that that due to much loss of discharge energy in the discharge gaps and reduction of the ejecting force on the melted materials, machining efficiency is better.

Graph 4.2 represents the interactive effect of all the factors upon MRR. First graph of the six shown graphs give the interactive effect of current and pulse on-time. Second one gives the effect of current and pulse off-time, third one gives the effect of pulse on-time and pulse off-time and so on. These graphs indicates that Graphite as additive gives the best result for hardness for a particular value of the current, pulse on-time and pulse off-time. Maximum MRR is at highest combination level of current and pulse on-time. Same the results for current and pulse off-time. For combination with dielectric, graphite with highest level value of current, pulse on-time and pulse off-time gives the higher MRR.

Table 4.3 Average values at factor levels for MRR for graphite

Level	I		Pulse on		Pulse off	
	Raw data	SNR	Raw data	SNR	Raw data	SNR
L1	71.89	37.13329	73.00333	37.26612	72.77667	37.2397
L2	73.11333	37.27979	72.78	37.23967	72.78	37.23967
L3	73.55667	37.33242	72.77667	37.2397	73.00333	37.26612

From the above graph it is found that the optimum combination for micro hardness is $A_3B_3C_3D_2$ which is not there in the experimental set up. So the theoretical optimum value is required to be found. The table shown above gives the average values for all the three levels of the factors current, pulse on-time and pulse off-time for the graphite powder (As D_2 stands for the dielectric with graphite as an additive). Mean value of SNR for Material Removal Rate is 37.06224.

The formula used for calculating the theoretical optimal value η_{opt} is given as under;

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

$$= 37.06224 + (37.33242-37.06224) + (37.2397-37.06224) + (37.26612-37.06224)$$

$$= 37.06224 + 0.27018 + 0.17746 + 0.20388$$

$$= 37.71376$$

And the corresponding value of micro-hardness is given by;

$$y_{opt}^{2} = \frac{1}{10^{\frac{-\eta_{opt}}{10}}} = 5907.123$$

or $y_{opt} = 76.85781$

Thus the optimal (theoretical) value of the micro hardness for this set up of experimentation is 76.85781.

Table 4.4 ANOVA table of Material Removal Rate

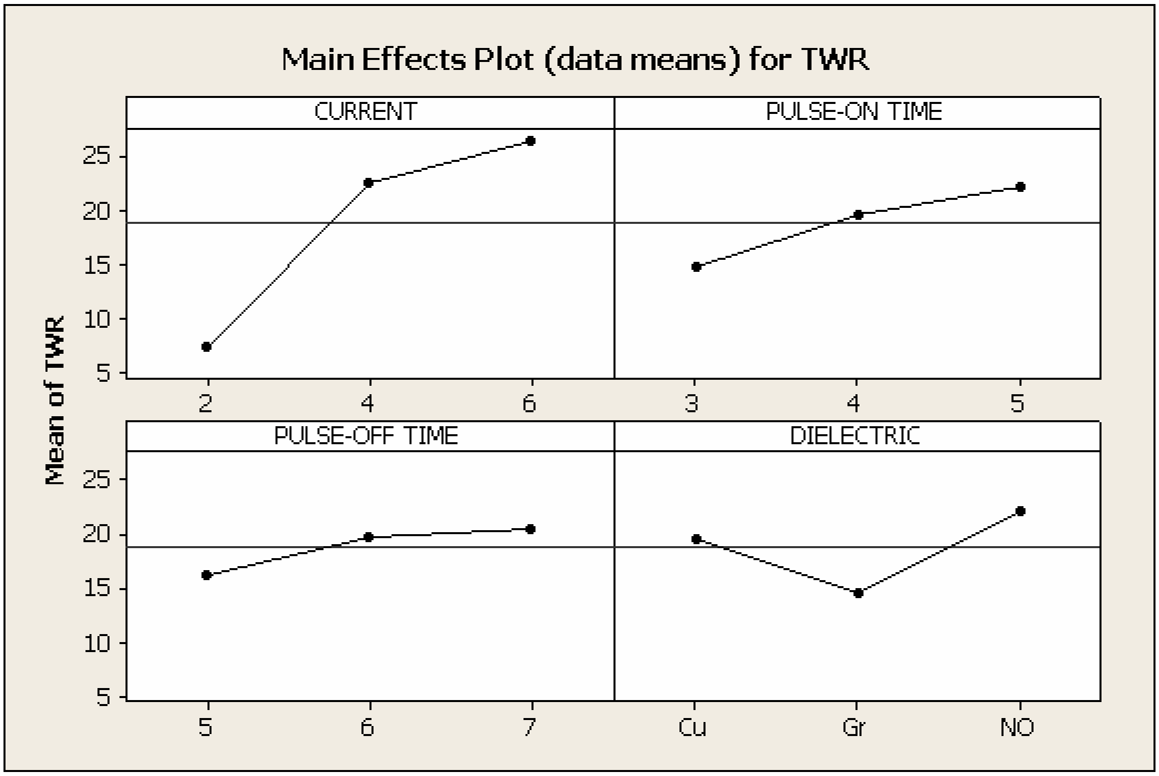
Source	SS	DOF	Variance	F test	F critical	SS'	C (%)	
Current (A)	6.095556	2	3.047778	56.36301	5.14	5.985079	50.80713	**S**
Pulse On time (B)	0.56	2	0.28	5.178082	5.14	0.449524	3.815992	**S**
Pulse Off time (C)	0.886667	2	0.443333	8.19863	5.14	0.77619	6.589053	**S**
Dielectric (D)	2.406667	2	1.203333	22.25342	5.14	2.29619	19.49228	**S**
A XB	0.231111	4	0.057778	1.068493	4.53			**NS**
A X C	0.217778	4	0.054444	1.006849	4.53			**NS**
A X D	1.057778	4	0.264444	4.890411	4.53	0.836825	7.103781	**S**
error	0.324444	6	0.054074					
Total	11.78	26				11.78	100	
e-pooled	0.773333	14	0.055238			1.885714	12.19177	**NS**

MRR

			A1			**A2**			**A3**			
			5.7			12.5			16			
		C1=2			C2=4			C3 = 6				**C1**
	Pon1=3	**0.2**			**0.5**			**1**			Poff1=5	9.7
B1			**0.3**			**1**			**1.5**		Poff2=6	
9.6				**0.6**			**2**			**2.5**	Poff3=7	
	Pon2=4		**0.5**			**1.5**			**1**		Poff1=5	**C2**
B2				**1**			**1.5**			**2.5**	Poff2=6	10.9
12		**1**			**1.5**			**1.5**			Poff3=7	
	Pon3=5			**0.5**			**2**			**2.5**	Poff1=5	
B3		**0.6**			**1**			**1.5**			Poff2=6	**C3**
12.6			**1**			**1.5**			**2**		Poff3=7	13.6
		No	Cu	Gr	No	Cu	Gr	No	Cu	Gr		
		8.8				10.3				15.1	**T=**	34.2
		D1				**D2**				**D3**		

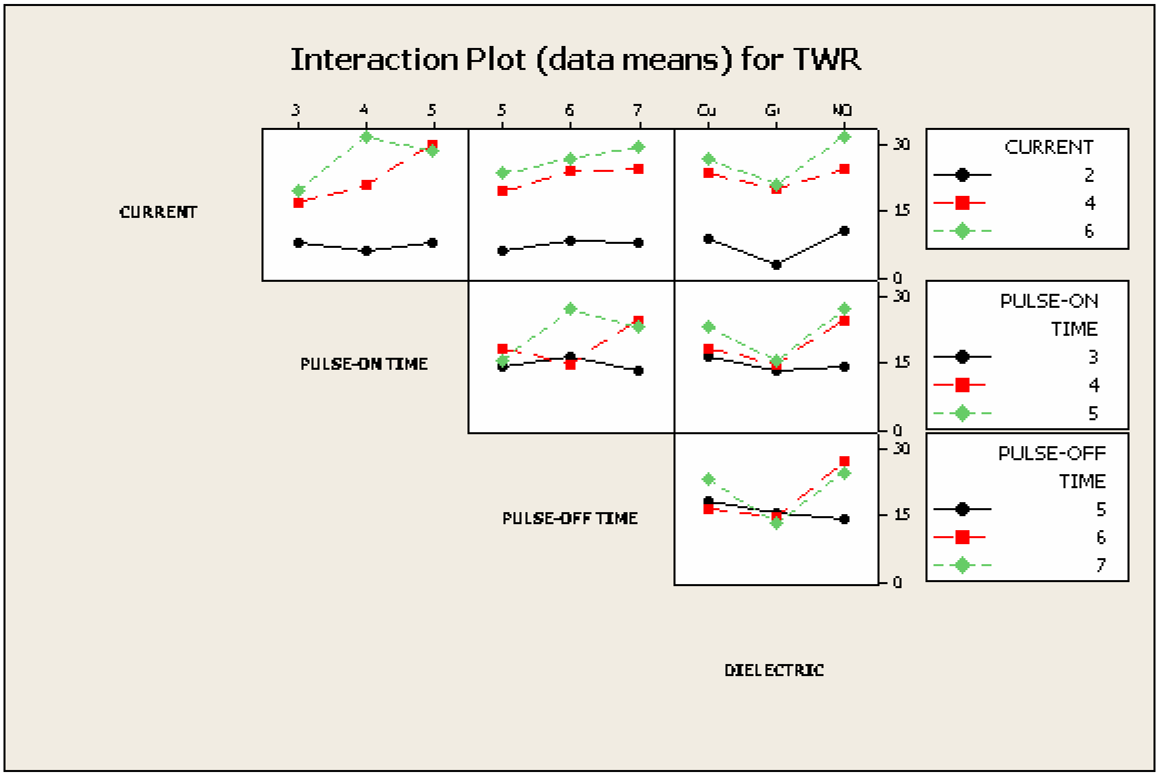
From the results of the ANOVA table, it is clear that all the four factors current, pulse on time, pulse off time and dielectric have effect on the material removal rate individually. The interaction between current and dielectric also has the significant effect upon the material removal rate. This interaction is important because current is directly proportional to the energy at discharge and by adding dielectric machining efficiency improves too. So, the combined effect of both becomes important. The other two interactions are not so much of importance as the F-test value is less than the F-critical, so they are non-significant. Out of all factors, current and dielectric has most significant effect on the Material removal rate. From these results, it is clear that the material removal rate increases with the addition of the powder in the dielectric and the increase in the current amperage.

4.2 Experimental results for TWR:



Graph 4.3 Effect of various factors on the TWR

Graph 4.3 shows the effect of various factors upon the Tool wear rate. Tool is made up of copper. It is clear from the graphs that TWR also increases with increase in current, pulse on-time and pulse off-time and powder suspended powders give better results than that of the kerosene only. Graphite suspended kerosene gives the better results that are lesser TWR than that of copper suspended dielectric.



Graph 4.4 Interaction plot for TWR

Graph 4.4 gives the interactive effect of various factors upon the Tool Wear Rate. It shows that for current and pulse on-time combination, with increase in the current value, TWR wear rate also increases and the TWR rate is highest for highest levels. It is clear 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 4.5 Average values at factor levels for TWR for graphite as additive

Level	I		Pulse on		Pulse off	
	Raw data	SNR	Raw data	SNR	Raw data	SNR
L1	3	-9.201	13.33	-20.75	13.33	-20.75
L2	20	-25.89	15	-20.704	15	-20.704
L3	21	-26.36	15.67	-20	15.67	-20

From the above graph it is found that the optimum combination for micro hardness is $A_1B_1C_1D_2$ which is not there in the experimental set up. So the theoretical optimum value is required to be found. The table shown above gives the average values for all the three levels of the factors current, pulse on-time and pulse off-time for the no powder as additive (As D_2 stands for the dielectric with graphite as an additive).

The formula used for calculating the theoretical optimal value η_{opt} is given as under;

$$\eta_{opt} = m + (m_{A1} - m) + (m_{B1} - m) + (m_{C1} - m)$$

$$= -23.6393 + (-9.201+23.6393) + (-20.75+23.6393) + (-20.75+23.6393)$$

$$= -23.6393 + 14.4383 + 2.8893 + 2.8893$$

$$= -3.4224.$$

And the corresponding value of TWR is given by;

$$y_{opt}^{\ 2} = 10^{\frac{-\eta_{opt}}{10}}$$

or y_{opt} = 1.483..

So the optimal value of TWR is 1.483 for this experimental set up.

4.5a ANOVA Table for Tool wear rate

TWR

			A1			**A2**			**A3**				
			67			203			238				
		C1=2			C2=4			C3 = 6				**C1**	
	Pon1=3	**10**			**13**			**20**			Poff1=5		146
B1			**10**			**20**			**20**		Poff2=6		
133				**4**			**18**			**18**	Poff3=7		
	Pon2=4		**6**			**20**			**30**		Poff1=5	**C2**	
B2				**3**			**17**			**25**	Poff2=6		177
176		**10**			**25**			**40**			Poff3=7		
	Pon3=5			**2**			**25**			**20**	Poff1=5		
B3		**12**			**35**			**35**			Poff2=6	**C3**	
199			**10**			**30**			**30**		Poff3=7		185
		No	Cu	Gr	No	Cu	Gr	No	Cu	Gr			
		200				176				132	**T=**		508
		D1				**D2**				**D3**			

From the ANOVA table, the important factors which affect the Tool wear rate are all the four input parameters i.e. current, pulse on time, pulse off time and dielectric. Also the interaction between current and pulse on time is significant among all the interactions considered. Out of all the factors, current has the maximum impact upon the Tool wear rate. From the graphical results it is clear that as the current increases, tool wear rate also increases. Current is directly proportional to discharge energy and pulse on-time means the time for which the tool-job are under the effect of spark energy. With increase in current and pulse on-time, tool wear rate also increases and hence the same is the result from ANOVA table.

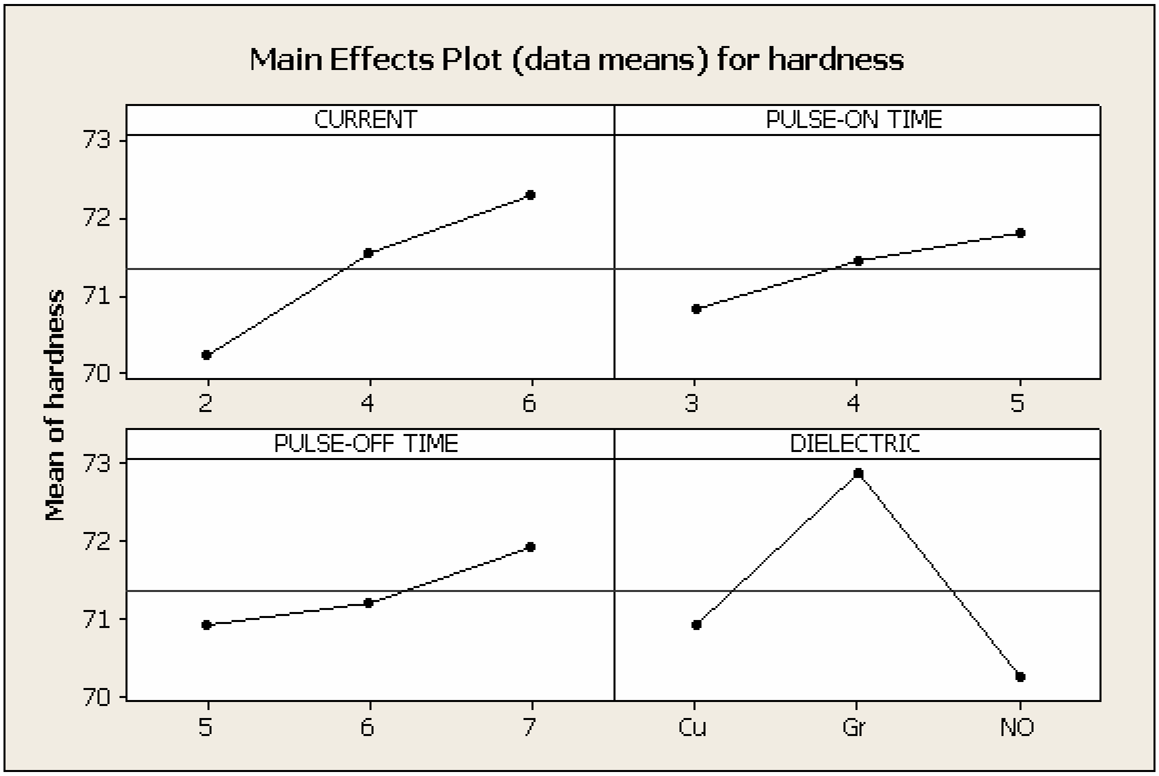
Source	**SS**	**DOF**	**Variance**	**F test**	**F critical**	**SS'**	**C (%)**	
Current (A)	1813.407	2	906.7037	129.5291	5.14	1800.444	64.71591	**S**
Pulse On time (B)	249.4074	2	124.7037	17.81481	5.14	236.4444	8.498855	**S**
Pulse Off time (C)	94.2963	2	47.14815	6.73545	5.14	81.33333	2.923478	**S**
Dielectric (D)	264.2963	2	132.1481	18.87831	5.14	251.3333	9.034027	**S**
A XB	269.9259	4	67.48148	9.640212	4.53	244	8.770435	**S**
A X C	16.37037	4	4.092593	0.584656	4.53			**NS**
A X D	32.37037	4	8.092593	1.156085	4.53			**NS**
error	42	6	7					
Total	2782.074	26				2782.074	100	
e-pooled	90.74074	14	6.481481			981.6296	6.057298	**NS**

4.3 Experimental results for Micro hardness

Table 4.6 shown below gives the experimental results for micro hardness. Three readings were taken on the hardness tester for each specimen after performing the experiment. In the table mean of all the three readings taken was calculated. Signal to noise ratios were also calculated with ‘Higher the Best’ approach. Mathematical relation for calculating the Signal to noise ratio using the ‘Higher the Best’ approach has already been described earlier.

Table 4.6 Experimental values for micro-hardness

S.No.	y_1	y_2	y_3	$\bar{y}$	**SNR**
1	68	69	70	69	36.77516
2	69	69	70	69.33333	36.81824
3	71	72	72	71.66667	37.10578
4	69	71	70	70	36.90019
5	71	71	73	71.66667	37.10412
6	68	69	71	69.33333	36.81466
7	71	72	74	72.33333	37.18293
8	68	69	70	69	36.77516
9	69	70	70	69.66667	36.8599
10	68	70	70	69.33333	36.8164
11	69	70	71	70	36.90019
12	73	74	74	73.66667	37.34488
13	70	71	72	71	37.02344
14	72	72	75	73	37.26165
15	70	70	73	71	37.02009
16	71	73	74	72.66667	37.22283
17	71	72	71	71.33333	37.06528
18	71	72	73	72	37.14497
19	69	69	70	69.33333	36.81824
20	70	71	72	71	37.02344
21	73	74	75	74	37.38305
22	71	71	72	71.33333	37.06528
23	73	74	74	73.66667	37.34488
24	71	72	73	72	37.14497
25	72	73	75	73.33333	37.30229
26	71	72	73	72	37.14497
27	73	74	75	74	37.38305

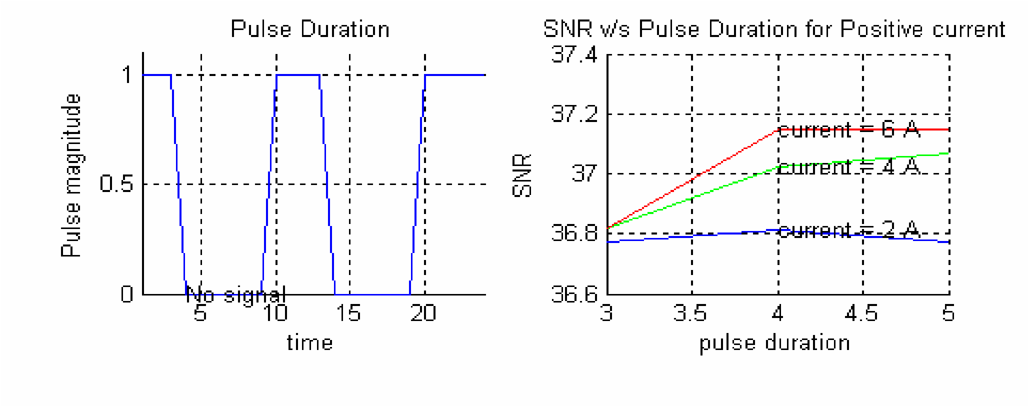


Graph 4.5 Effect of various factors on Micro-hardness

Graph 4.6 Interaction plot for micro-hardness

Graph 4.5 gives the effect of various factors i.e. current, pulse on-time, pulse off-time and dielectric on the micro-hardness of the finished surface. In this case also, increase in current, pulse on-time and pulse off-time values, there is increase in the micro hardness of the surface and the graphite suspended dielectric gives the highest micro hardness than that of copper suspended dielectric and dielectric with no powder suspended.

Graph shown above, represents the effect of various factors upon the micro hardness of the machined surface. From the graph it is clear that with increase in current, hardness increases. Along with pulse on-time, dielectric and pulse off-time, this trend has also been followed. For the combination of pulse on-time and pulse off-time, hardness increases for first set of values, then decreases and then again increases. When powder is suspended into the dielectric, hardness is maximum for the graphite suspended dielectric.



Graph 4.7 SNR when no powder is used

Table 4.7 Average values at factor levels for micro hardness for graphite

Level	I		Pulse on		Pulse off	
	Raw data	SNR	Raw data	SNR	Raw data	SNR
L1	71.89	37.1309	73.11	37.2779	72.78	37.2360
L2	73.11	37.2765	72.78	37.2369	72.78	37.2369
L3	73.67	37.3434	72.78	37.2360	73.11	37.2279

From the above graph it is found that the optimum combination for micro hardness is $A_3B_3C_3D_2$ which is not there in the experimental set up. So the theoretical optimum value is required to be found. The table shown above gives the average values for all the three levels of the factors current, pulse on-time and pulse off-time for the graphite powder (As D_2 stands for the dielectric with graphite as an additive).

The formula used for calculating the theoretical optimal value η_{opt} is given as under;

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

$$= 37.0647 + (37.3434-37.0647) + (37.2360-37.0647) + (37.2279-37.0647)$$

$$= 37.0647 + 0.2787 + 0.1713 + 0.163$$

$$= 37.6777$$

And the corresponding value of micro-hardness is given by;

$$y_{opt}{}^{2} = \frac{1}{10^{\frac{-\eta_{opt}}{10}}} = 5858.278$$

or $y_{opt} = 76.53939$

Thus the optimal (theoretical) value of the micro hardness for this set up of experimentation is 76.53939.

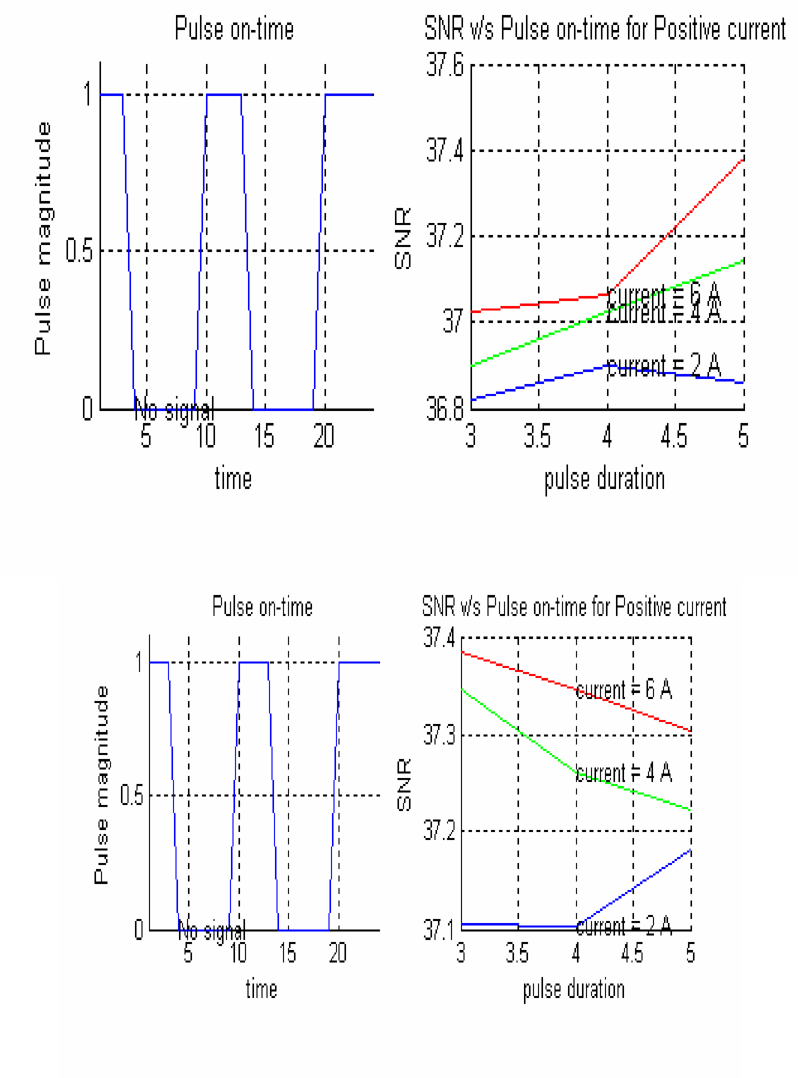
Table 4.8 ANOVA table of Micro-hardness

Source	SS	DOF	Variance	F test	F critical	SS'	C (%)	
Current (A)	19.87227	2	9.936133	49.47452	5.14	19.4417	27.8420	**S**
Pulse On time (B)	4.6014	2	2.3007	11.45577	5.14	4.17078	5.97290	**S**
Pulse Off time (C)	4.768089	2	2.384044	11.87076	5.14	4.33747	6.21161	**S**
Dielectric (D)	33.70069	2	16.85034	83.90213	5.14	33.2701	47.6454	**S**
A XB	1.349467	4	0.337367	1.679834	4.53			**NS**
A X C	3.871711	4	0.967928	4.819557	4.53	3.01048	4.31125	**S**
A X D	0.459844	4	0.114961	0.57242	4.53			**NS**
error	1.205	6	0.200833					
Total	69.82847	26				69.8285	100	
e-pooled	3.014311	14	0.215308			12.9460	8.01679	**NS**

As it is clear from the ANOVA table, for micro-hardness important parameters are all the factors and the interaction between the current and pulse off time. Also, as the pooled error is less than 15%, so the results are acceptable as per Taguchi standards. Out of the entire factor, dielectric has the most significant effect upon the micro-hardness. As the contribution is very less in case of interaction so its significance not clearly indicated

hardness

			A1			A2			A3			
			632			644			650.66			
		Current=2			Current=4			Current=6				C1
	Pon1=3	**69**			**69.33**			**69.33**			Poff1=5	638.32
B1			**69.33**			**70**			**71**		Poff2=6	
637.33				**71.67**			**73.67**			**74**	Poff3=7	
	Pon2=4		**70**			**71**			**71.33**		Poff1=5	C2
B2				**71.67**			**73**			**73.67**	Poff2=6	641
643		**69.33**			**71**			**72**			Poff3=7	
	Pon3=5			**72.33**			**72.67**			**73.33**	Poff1=5	
B3		**69**			**71.33**			**72**			Poff2=6	C3
646.33			**69.67**			**72**			**74**		Poff3=7	647.34
		No	Cu	Gr	No	Cu	Gr	No	Cu	Gr		
		632.32				638.33				656.01	T=	1926.66
		D1				D2				D3		



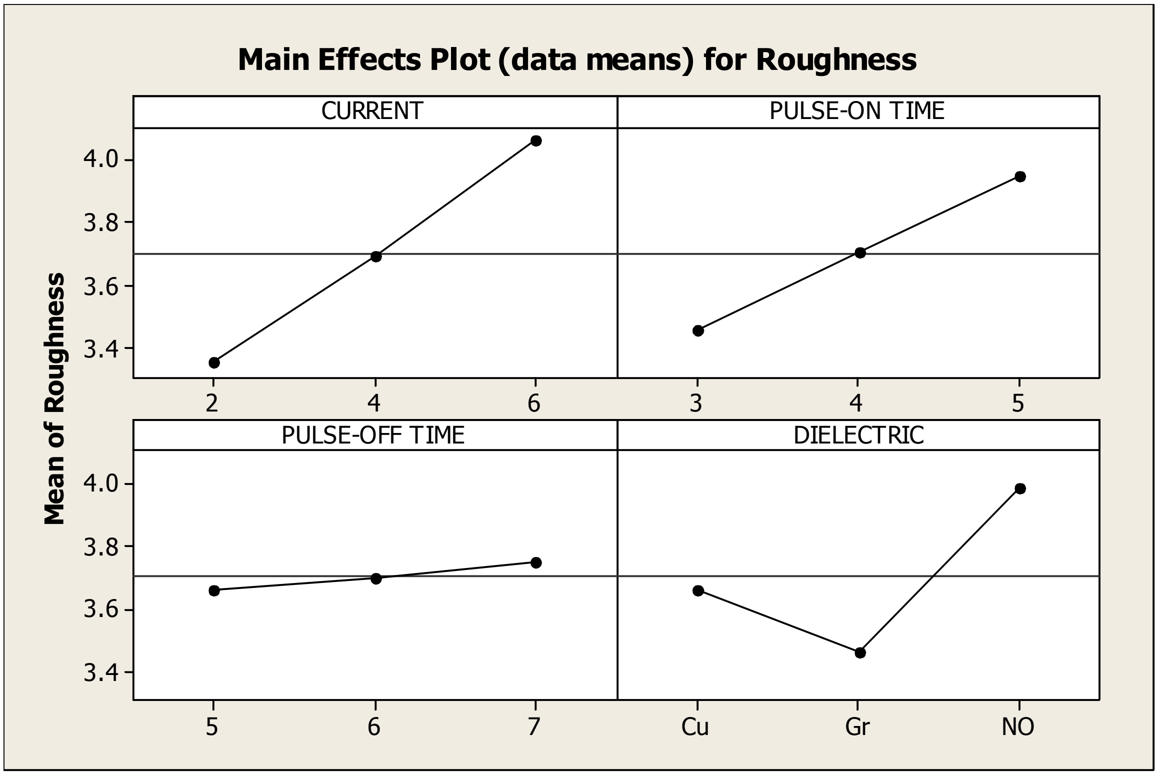
Graph 4.8 SNR plots when copper and graphite are used as additives respectively

The optimal value of micro hardness is also calculated from the SNR values for the optimal combination. This combination is obtained from the main effects plot for micro hardness. Pulse off-time means the time gap between two successive on-times. It is important for proper flushing and cooling down of work-piece. Material of the electrode is deposited during off-time, which increases the thickness of recast layer and thus hardness. So the interaction between current and pulse off-time is important.

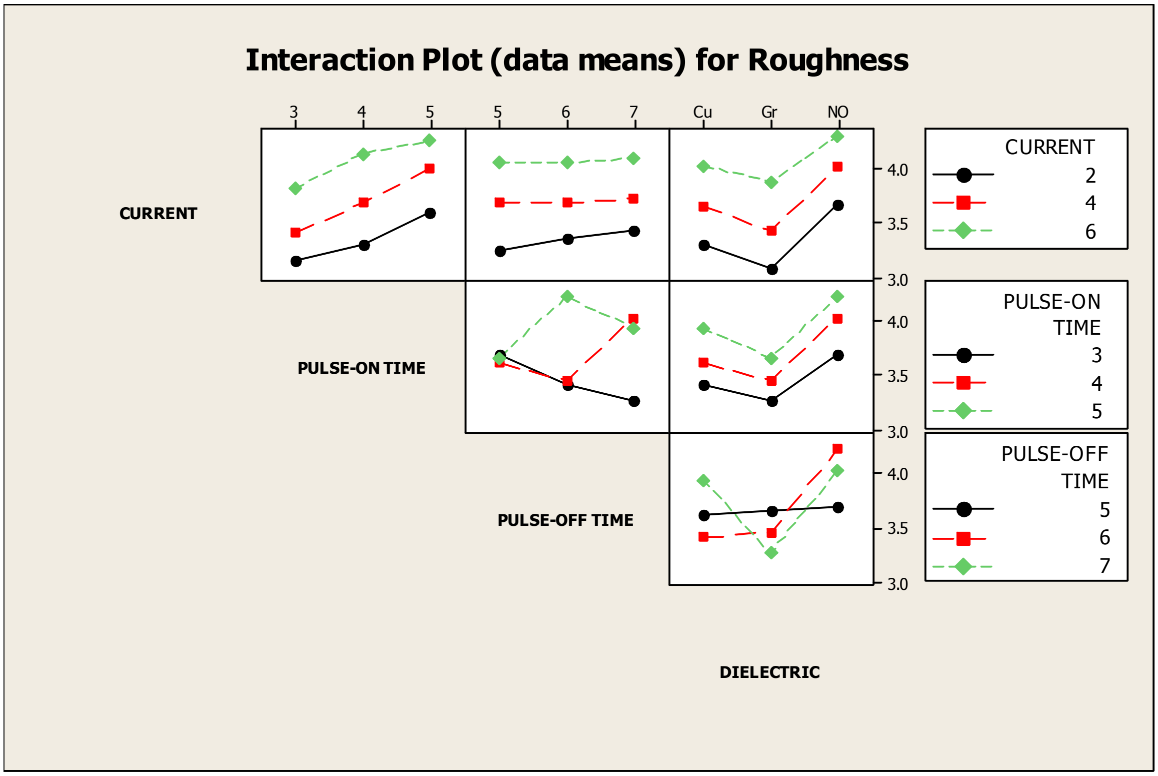
4.4 Experimental results for Surface roughness

S.No.	y_1	y_2	y_3	$\bar{y}$	SNR
1	3.23	3.42	3.49	3.38	-10.5829187
2	2.87	3.05	3.38	3.1	-9.84734285
3	2.74	2.92	3.31	2.99	-9.54083239
4	2.94	3.14	3.43	3.17	-10.0386391
5	2.86	2.98	3.34	3.06	-9.73368035
6	3.42	3.64	3.98	3.68	-11.3339412
7	3.06	3.18	3.42	3.22	-10.1664899
8	3.72	3.9	4.2	3.94	-11.9208774
9	3.42	3.58	3.92	3.64	-11.2362518
10	3.54	3.68	3.94	3.72	-11.4194702
11	3.18	3.3	3.54	3.34	-10.4836411
12	3.04	3.14	3.36	3.18	-10.0562088
13	3.43	3.58	3.88	3.63	-11.2096528
14	3.22	3.36	3.62	3.4	-10.639885
15	3.76	3.92	4.32	4	-12.0562293
16	3.46	3.62	4.02	3.7	-11.3815949
17	4.02	4.24	4.64	4.3	-12.6848124
18	3.72	3.92	4.3	3.98	-12.0134978
19	3.8	3.96	4.24	4	-12.050166
20	3.62	3.76	4.02	3.8	-11.6039249
21	3.44	3.58	3.87	3.63	-11.2086884
22	3.84	3.96	4.35	4.05	-12.1616326
23	3.72	3.9	4.11	3.91	-11.8507446
24	4.2	4.38	4.68	4.42	-12.9171508
25	3.92	4.06	4.26	4.08	-12.218279
26	4.18	4.4	4.74	4.44	-12.9593344
27	4.12	4.2	4.31	4.21	-12.4871282

Table 4.9 Average values for Surface roughness



Graph 4.9 Effect of various factors on Surface Roughness



Graph 4.10 Interaction plot for Surface Roughness

Graph 4.9 shows the effect of various factors i.e. current, pulse on-time, pulse off-time and dielectric upon the roughness of the surface. Roughness of the surface increases with increase in the current, pulse on-time and pulse off-time as it is clear from the main effect graphs. Graphite suspended kerosene gives the best surface finish followed by copper suspended dielectric and kerosene with no kerosene suspended in it.

Graph 4.10hows the interactive effect of all the factors i.e. input parameters (current, pulse on-time and pulse off-time) upon the response i.e. Surface roughness. Form graphs it is clear that surface roughness increases with increase in current and pulse on-time. The effect of combination of current and pulse on-time and pulse off-time and pulse on-time. When the dielectric is added to the kerosene, for lower values of current graphite gives the minimum surface roughness, but for larger values, it graphite powder gives higher roughness. But on average, graphite gives the minimum surface roughness for current values. Similarly, with pulse on-time and pulse off-time, on average basis, graphite suspended dielectric gives the minimum surface roughness.

Table 4.10 Average values at factor levels for surface roughness for graphite as additive

Level	I		Pulse on		Pulse off	
	Raw data	SNR	Raw data	SNR	Raw data	SNR
L1	3.09	-9.8137	3.2667	-10.2686	3.2667	-10.2686
L2	3.427	-10.6926	3.4567	-10.7415	3.6667	-11.2555
L3	3.873	-11.7593	3.6667	-11.2555	3.4567	-10.7415

From the above graph it is found that the optimum combination for micro hardness is $A_1B_1C_3D_2$ which is not there in the experimental set up. So the theoretical optimum value is required to be found. The table shown above gives the average values for all the three levels of the factors current, pulse on-time and pulse off-time for the no powder as additive (As D_3 stands for the dielectric with graphite as an additive).

The formula used for calculating the theoretical optimal value η_{opt} is given as under;

$$\eta_{opt} = m + (m_{A1} - m) + (m_{B1} - m) + (m_{C3} - m)$$

$$= -11.3260 + (-9.8137 + 11.3260) + (-10.2686 + 11.3260) + (-10.7415 + 11.3260)$$

$$= -11.3260 + 1.5123 + 1.0574 + 0.5845$$

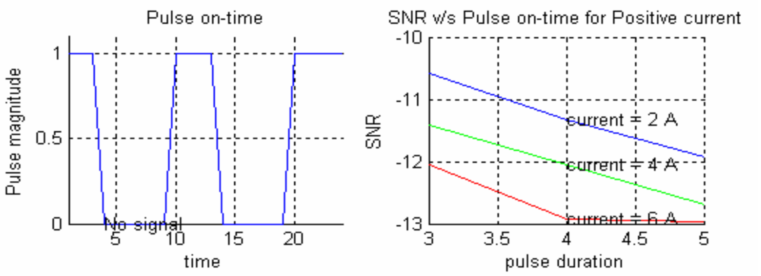
$= -8.1718$

And the corresponding value of surface roughness is given by;

$$y_{opt}^{2} = 10^{\frac{-\eta_{opt}}{10}} = 6.564173$$

or $y_{opt} = 2.562064$.

So the optimal value of Roughness is 2.562064 for this experimental set up.



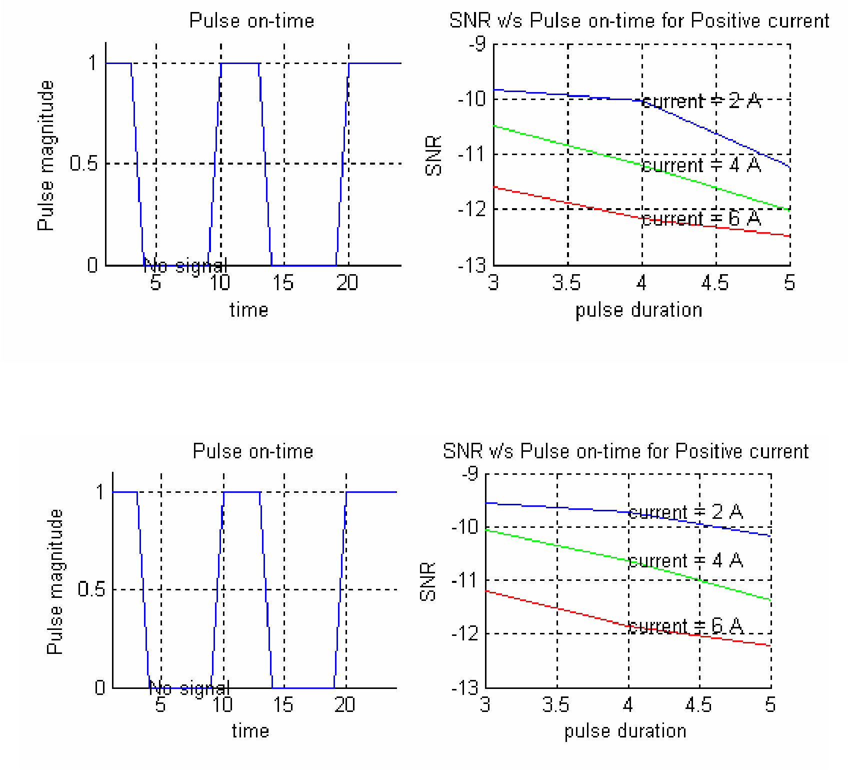
Graph 4.11 SNR plot when no powder is added

Table 4.11 ANOVA table of Surface Roughness

Source	SS	DOF	Variance	F test	F critical	SS'	C (%)	
Current (A)	2.248096	2	1.124048	672.9335	5.14	2.239651	47.5054	**S**
Pulse On time (B)	1.060941	2	0.53047	317.5765	5.14	1.052495	22.32455	**S**
Pulse Off time (C)	0.033985	2	0.016993	10.17295	5.14	0.02554	0.541724	**S**
Dielectric (D)	1.259563	2	0.629781	377.031	5.14	1.251117	26.53754	**S**
A XB	0.052815	4	0.013204	7.904656	4.53	0.035924	0.761983	**S**
A X C	0.021637	4	0.005409	3.238359	4.53			**NS**
A X D	0.027459	4	0.006865	4.109756	4.53			**NS**
error	0.010022	6	0.00167					**NS**
Total	4.714519	26				4.714519	100	
e-pooled	0.059119	14	0.004223			2.474868	2.328796	

Roughness

			A1			**A2**			**A3**			
			30.18			33.25			36.54			
		C1=2			C2=4			C3 = 6				**C1**
	Pon1=3	**3.38**			**3.72**			**4**			Poff1=5	32.95
B1			**3.1**			**3.34**			**3.8**		Poff2=6	
31.14				**2.99**			**3.18**			**3.63**	Poff3=7	
	Pon2=4		**3.17**			**3.63**			**4.05**		Poff1=5	**C2**
B2				**3.06**			**3.4**			**3.91**	Poff2=6	33.29
33.32		**3.68**			**4**			**4.42**			Poff3=7	
	Pon3=5			**3.22**			**3.7**			**4.08**	Poff1=5	
B3		**3.94**			**4.3**			**4.44**			Poff2=6	**C3**
35.51			**3.64**			**3.98**			**4.21**		Poff3=7	33.73
		No	Cu	Gr	No	Cu	Gr	No	Cu	Gr		
		35.88				32.92				31.17	**T=**	99.97
		D1				**D2**				**D3**		



Graph 4.12 SNR plots when copper and graphite used as additives

From the ANOVA for the Surface roughness, the significant parameters that affect the surface roughness are all the four factors and the interaction between the current and the pulse off time. In this case the pooled error is again less than 15%. So the results are acceptable according to Taguchi standards. Out of all the factors current, pulse on time and dielectric have the most significant effect on the surface roughness. The interaction between current and pulse on-time is significant, but as its contribution is very less, so it is not very much clear from the graphs generated and shown above. Surface roughness has very little contribution, which is clearly depicted from the graphs for roughness also, as its variation is symmetrical about the mean value of the variation.

CHAPTER 5
RESULTS AND CONCLUSIONS

This chapter includes the summary, results and conclusions of the experimental work carried out. Shortcomings of the present study and scope of the future research work in this field has also been given in this chapter.

5.1 Summary

The objective of the work carried out is to study the effect of powder mixed dielectric (PMEDM) upon two very important parameters of the Electric Discharge Machining i.e. Material Removal Rate and Tool Wear Rate. Also the effect was studied on the Micro hardness and Surface roughness of the work-piece. For the purpose of experimentation EDM machine, which is installed in Machine Tool Laboratory at Thapar University has been utilized. The machine has the capability to vary the polarity, peak current, pulse on-time, pulse off-time, pulse duration etc. Considering the capability of the machine and the output required for the experimentation, peak current, pulsed on-time and pulse off-time were decided to be taken as the variable and all the other factors have to be kept fixed. Two powders were mixed into the dielectric kerosene in order to study the effect of powder mixed dielectric on machining parameters decided. These powders were copper and graphite. Physical properties of the powders were given in Appendix C. Polarity was kept constant throughout the experimentation as positive. To obtain the desired results with minimum possible number of experiments, Taguchi method has been employed. Using Taguchi, L27 orthogonal array has been selected and the experiments have been designed. After performing the experiments, results of the experimentation have been analyzed and graphs for effect of various input variables upon output parameters and for Signal to noise ratio have been studied and discussed using ANOVA (Analysis of variance). Also the optimum combination of input variables has been determined which will give the best results for output parameters using signal to noise ratios. The results and conclusions along with limitations and future scope of work has been given in the next section of the chapter.

5.2 Results

- Test results have shown that there is significant effect of powder mixed dielectric upon all the output parameters selected. Reason for improvement in results due to addition of powder is that due to much loss of discharge energy in the discharge gaps and reduction of the ejecting force on the melted materials, surface roughness is lower than that of conventional EDM. Machining efficiency has also been improved with proper selection of the parameters.

- Material removal rate is higher with graphite as an additive in comparison to that of copper. Reason for this is that due to low thermal conductivity of graphite, electrode material is not allowed to absorb more amount of heat. Therefore the TWR is lower and most of the heat is used to remove material. As a result, material removal rate will be higher.

- Tool wear rate is higher with copper as an additive.

- The Surface roughness generated by Copper powder is more as compared to Graphite powder when experimentation is done. Reason for this is that thermal and electrical conductivity of the copper is more than that of the graphite powder.

- Micro hardness is more in the case of the graphite powder because it has lower thermal conductivity and graphite powder contaminated in large amounts on the surface of the work piece.

5.3 Conclusion

From the study it has been concluded that the PMEDM (Powder Mixed Electric Discharge Machining) has significant effect on the material removal rate and tool wear rate as well as upon surface properties like surface roughness and micro hardness. With the addition of the powders in the dielectric, material removal rate has been increased to a great extent and the tool wear rate has been reduced. Graphite gives better results in terms of Material removal rate and tool wear rate as well as in case of hardness and roughness also in comparison to copper powder. So, it is concluded and suggested to use graphite as an additive for PMEDM in comparison to that of copper. Thus, PMEDM can be employed for making micro structures and compositions which are otherwise difficult with other processes like casting, forging, etc.

5.4 Limitations

- Current signal was kept at 2, 4 and 6 amperes only. Current can be varied from 0 to 12 amperes. Though other values of the peak current can also be taken for the experimentation.

- Polarity was kept as positive i.e. work-piece has been acted as anode and tool has been worked as cathode.

- Pulse-on-time was altered to 3, 4 and 5 for each current signal. Pulse on-time has the higher range of variation and whole range was not covered during the experimentation.

- Pulse-off-time was altered to 5, 6 and 7 for each current signal. It has higher range of variation which can not use for the study.

- In Electric Discharge Machining a large number of dielectrics exist, but in this experimental work kerosene was the only dielectric used.

- Copper and Graphite were the only powders used. There are number of powders such as nickel, titanium, vanadium etc. have not been used for conducting experiments.

- Only copper tool and EN-31 die steel work piece were used. Plenty of other options are available for both tool material and the work-piece, which have not been used for this work.

5.5 Scope of Future work

- Some parameters like polarity were kept constant, these can also be varied and their effect studied. For this particular experimental set-up, Workpiece is kept positive, whereas tool act as cathode (negative) i.e. straight polarity has been used.

- The process can be repeated on other material using other electrodes. In this experimental setup, EN-31 is the only work-piece material, which has been used. Also the material of the electrode is same for the whole experimentation i.e. copper electrode. Many other electrode materials are available and widely used in various applications and they can be used if the futures work.

- Different types of dielectric powders can be used. In this work, only copper and graphite powders were used. There are several other powders such as nickel, titanium, vanadium etc. which can be used in future practices.

- The debris which is left in the dielectric can be collected and analyzed to see the results.

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Appendix

Appendix A

Technical Data of EDM

1. Electrical Data	
Type	M
Supply Volts(V)	415 V, 3ϕ, 50 Hz.
Taps	373 V, 415 V, 457V
Mains voltage tolerance	± 10%
Connected Load (KVA)	3
Power Factor	Approx. 0.8
2. **Working Parameters**	
Machine current maximum (A)	12
Open gap output voltage (V)	$135 \pm 5\%$
Rotary switch Current Range	3 ranges of 4 Amp. each
Rotary knob current adjust	Fine current adjustment from 0-4 Amperes in each current range
Pulse Duration	2 μs to 650 μs
Height	1000 mm
Width	550 mm
Depth	690 mm
Weight	135 kg

Appendix B

List of controls

S.No.	**List of Controls**
1	Rotary Switch (Mains)
2	Indicator Lamps (Three Phase)
3	Rotary Switch (Finish)
4	Rotary Switch (Pump)
5	Rotary Switch (Current range)
6	Rotary Knob (Current Adjust)
7	Ammeter (Gap Control)
8	Rotary Switch (Base)
9	Rotary Switch (Duration)
10	Indicator (Gap)
11	Rotary Potentiometer (Gap Control)
12	Toggle Switch (Soft Pulse)
13	Indicator Lamp (Spark)
14	Push Button (Spark)
15	Toggle Switch (Auto flush)
16	Rotary Potentiometer (Sparking Time)
17	Rotary Potentiometer (Lifting Time)
18	Indicator lamp
19	Push Button Red (off)
20	Rotary Switch (Auto/Man)
21	Push Button (Up/Down)
22	Indicator Lamp (Interlock)
23	Rotary Switch (Ignition)
24	Indicator (Pump on)
25	Push Button (Auto Pos)
26	Indicator Lamp (Autopos)
27	Piezo Ceramic Alarm (Buzzer)

28	Toggle Switch (Buzzer Select)
29	Decade Counter (Hour Counter)

Appendix C

Properties of Copper Powder

Mechanical Properties		**Conditions**		
		Phase	**Temp.** (K)	**Pressure** (Pa)
Density	8960 kg/m^3	Solid	298.15	0
Modulus of Elasticity	110.316 GPa	Solid	0	
Thermal Expansion Coefficient	1.650 × 10^{-5} /K	Solid	298.15	

Electrical Properties		**Conditions**	
		Temp. (K)	**Note**
Electrical Resistivity	1.673 × 10^{-8} Ω-m	293.15	

Thermal Properties		**Conditions**	
		Temp. (K)	**Pressure** (Pa)
Melting Temperature	1357.77 K		101325
Boiling Temperature	2835.15 K		101325
Critical Temperature	8280 K		
Fusion Enthalpy	208.7 J/g	0	101325
Heat Capacity	385 J/kg-K	298.15 more...	100000
Thermal Conductivity	401 W/m-K	300 more...	101325