STUDY ON OPTIMIZATION AND MACHINING CHARACTERISTICS OF ELECTRIC DISCHARGE MACHINING USING POWDER SUSPENSION DIELECTRIC FLUIDS

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DECLARATION

This is to certify that the thesis entitled **"A STUDY ON OPTIMIZATION AND MACHINING CHARACTERISTICS OF ELECTRIC DISCHARGE MACHINING USING POWDER SUSPENSION DIELECTRIC FLUIDS"** is an authentic record of my study carried out as requirements for the award of the degree of **Master of Engineering in Mechanical (Production and Industrial) Engineering** to **Thapar University, Patiala,** under the guidance of **Dr. Vinod Kumar Singla,** Associate Professor, Department of Mechanical Engineering, Thapar University, Patiala during **Jan 2012 to Dec 2012.** The matter embodied in this thesis has not been submitted in part or full to other university or institute for the award of any degree.

(AMAN ABROL)

This is to certify that the above declaration made by the student concerned is correct to the best of my knowledge and belief.

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ABSTRACT

EDM (Electric Discharge Machining) is a thermo-electric non-traditional machining process in which material removal takes place through the process of controlled spark generation between a pair of electrodes which are submerged in a dielectric medium.

The present study has been done to study the effect of different input parameters namely current, work piece material, dielectric medium, powder, pulse on time, tool angles, powder concentration on the MRR, TWR and WR. The effect of various input parameters on output responses is analyzed using statistical techniques such as ANOVA. Optimization and verification of the process parameters and the modeling of the results is done by applying Regression Analysis. Surface roughness and geometric accuracy has also been studied. XRD and microstructure analysis has been performed to understand the form and deposition on the surface of the workpiece material. Main effect plots for the significant factors and S/N ratio have been used to determine the optimal design for output response.

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ABBREVIATIONS

ANOVA	Analysis of Variance
EDM	Electric Discharge Machining
PMEDM	Powder Mixed Electric Discharge Machining
MRR	Material Removal Rate
TWR	Tool Wear Rate
SEM	Scanning Electron Microscope
XRD	X- Ray Diffraction
S/N	Signal to Noise Ratio

NOTATIONS

OA	Orthogonal Array
A	Dielectric
B	Workpiece Material
C	Angle
D	Concentration
E	Current
F	Pulse on time
G	Powder
CI	Confidence Interval
SS	Sum of Squares
ALLOY	Aluminium- Copper Alloy
MMC	Aluminium-Silicon Carbide Composite
Si	Silicon Powder
Cu	Copper Powder

CHAPTER 1

INTRODUCTION

There has been tremendous improvement in engineering materials since the Second World War. In this revolution, the discovery and development of new materials and alloys of characteristics suitable for aerospace, nuclear and other new industries is taking place. The advent of these new materials which are high strength temperature resistant material as well as increasingly complex part configurations has resulted in the creation of new, unique family of manufacturing processes known as Non-Conventional/Non-Traditional Machining Processes.

1.1 Introduction to Non-Traditional Machining

Machining removes certain parts of the work pieces to change them to final parts. Machining nowadays has been classified in two types: (1) Traditional Machining (2) Non-Traditional Machining. Traditional Machining, also known as conventional machining requires the presence of a tool that is harder than the work piece to be machined. This tool should be penetrated in the work piece to a certain depth. Moreover, a relative motion between the tool and work piece is responsible for forming or generating the required shape.

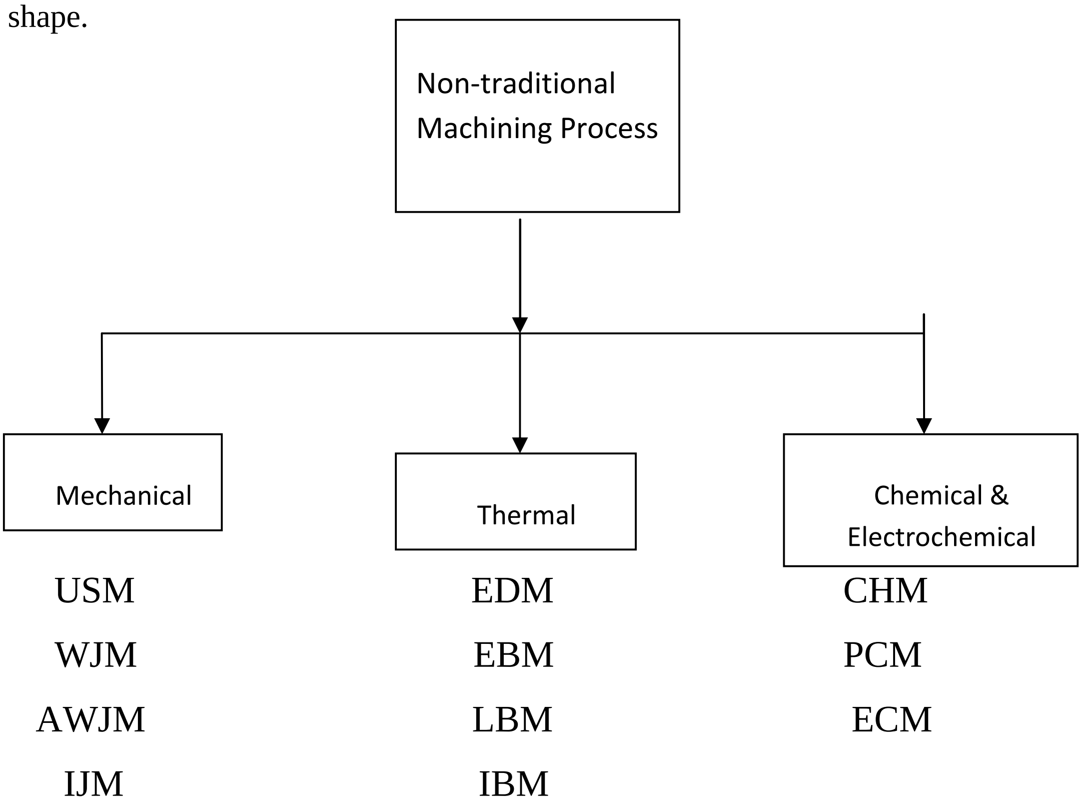


Figure: 1.1 Classification of Non-Traditional Machining Processes [1]

The absence of any of these elements in any machining process such as the absence of tool-work piece contact or relative motion, makes the process a non-traditional or non-conventional one [1].Non-conventional machining processes are well established in modern manufacturing industries as they are capable of machining hard materials. Non-conventional machining processes are classified according to the machining action which helps in material removal from the work piece. The material removal mechanism, machining system components, process variables, technological characteristics, and industrial applications are different for all these processes [1].

1.2 Electrical Discharge Machining (EDM)

EDM is one of the most extensively used non-conventional material removal processes. In this process, the material is removed by a succession of electrical discharges, which occur between the electrode and the workpiece. There is no direct contact between the electrode tool and the workpiece. These are submersed in a dielectric liquid such as kerosene or deionised water. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage. The electrical discharge machining process is widely used in the aerospace, automobile, die manufacturing and moulds industries to machine hard metals and its alloy[7,8].

1.3 History of EDM

The Russians are usually given the credit for discovering the EDM process in 1943. Lazarenko is the name that is associated with the process first called Spark Erosion, these days referred to as EDM. In 1770's, the English scientist Priestley discovered the eroding effect of electrical discharges. More than one hundred year was to pass before some practical use was made of the discovery. During an investigation of how to suppress the erosion of electrical switch contacts, the Soviet scientists B.R.Lazarenko and N.I. Lazarenko had an idea to use the destructive effect of the electrical charge in a controlled manner for machining recently developed metals that where proving to be difficult to machine. Soon thereafter, they developed a working procedure with spark erosion, where an electrical discharge in a dielectric liquid takes place between two electrodes [2].

1.4 Working Principle of EDM

The machining process involves controlled erosion of electrically conducting materials by the initiation of rapid and repetitive electrical spark discharge between the tool (or cathode) and the workpiece (or anode) separated by a dielectric fluid medium. When discharge takes place between two points of the anode and the cathode, the intense heat generated near the zone melts and evaporates the materials in the sparking zone. For effective machining, the workpiece and the tool are submerged in a dielectric fluid. A suitable gap, known as spark gap, is maintained between the tool and the workpiece to cause spark discharge. The sparks are made to discharge at a high frequency with a suitable source. Since the spark occurs at the spot where the tool and the workpiece surfaces are the closest and the spot changes after each spark, so the spark travels all over the surface. This results in a uniform material removal all over the surface, and finally the work face conforms to the tool surface [3].

1.5 Powder Mixed EDM

The demands for high machining precision with low surface roughness at relatively high machining rates arise in die, mould and tool manufacturing industries. To fulfil these requirements, a relatively new advancement in the direction of process capabilities is the addition of powder in the dielectric fluid of EDM. This process is called Powder Mixed EDM (PMEDM) or Additive EDM. It is a type of Hybrid Machining Process. Hybrid machining in EDM make use of combined advantages and to reduce some negative effects. The combined process produces better performance as compared to individual process machining. The results show that the PMEDM improves the surface finish, surface quality. In this process, a suitable material in fine powder form is mixed into the dielectric fluid of EDM. The added powder improves the breakdown characteristics of the dielectric fluid, i.e. insulating strength of the dielectric fluid decreases and consequently, the spark gap distance between the electrode and workpiece increases. Enlarged spark gap distance makes the flushing of debris uniform. As a result, the process becomes more stable thereby improving machining rate and surface finish [4].

1.6 Working of PMEDM

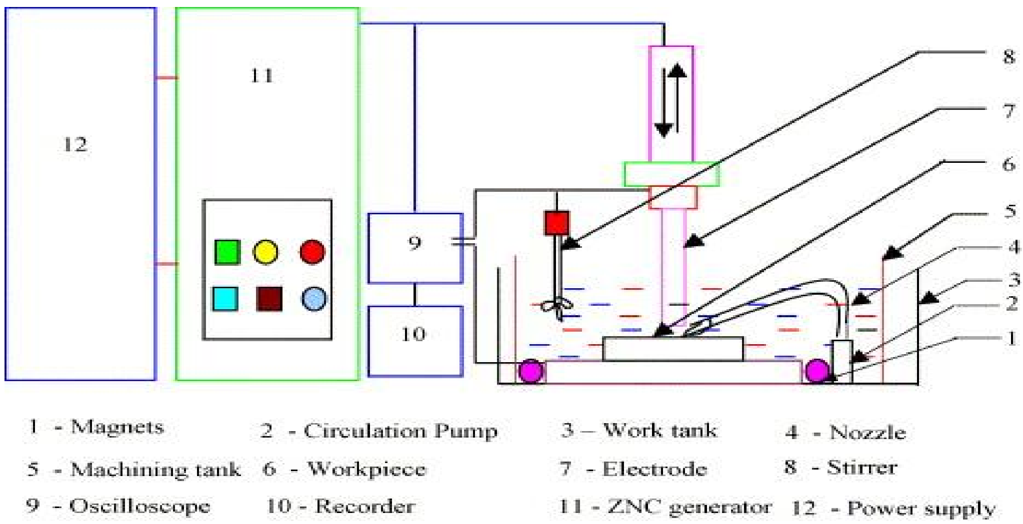


Figure: 1.2 Schematic of PMEDM [4]

In this process, a suitable material in powder form like aluminium, chromium, graphite, silicon, copper or silicon carbide is mixed into the dielectric fluid either in the same tank or separate tank. For better circulation of the powder mixed dielectric, a stirring system is used. The experimental setup consists of a machining tank which is filled with dielectric fluid. It is placed in the work tank of EDM and the machining is performed in this container. A workpiece fixture assembly is placed on it to hold the workpiece. To avoid particle setting, a stirring mechanism is incorporated. A small dielectric pump is installed for proper circulation of the powder mixed dielectric fluid into the discharge gap. The distance between powder mixed dielectric suction point and nozzle outlet is kept as short as possible in order to ensure the complete suspension of powder in the dielectric gap.

When a voltage of 80-320 V is applied between the electrode and the workpiece facing each other, electric field is created. The powder gets energized and behaves in a zig-zag fashion. These charged particles are accelerated by the electric field and act as conductors. The conductive particles promote breakdown in the gap and increase the spark gap between tool and the workpiece. As a result, a series discharge starts under the electrode area. The faster sparking within a discharge takes place and the material removal rate (MRR) increases. At the same time, the added powder modifies the plasma channel. The plasma channel becomes enlarged and widened. The sparking is uniformly distributed among the powder particles, hence electric density of the spark decreases. Due to uniform distribution of sparking among the powder particles, shallow craters are produced on the workpiece surface. This results in improvement in surface finish [4].

1.7 EDM Process Parameters

This section discusses the process parameters of EDM. This section focuses on effect of process parameters such as electrical and non-electrical parameters on various performance measures. Some of them are explained below:-

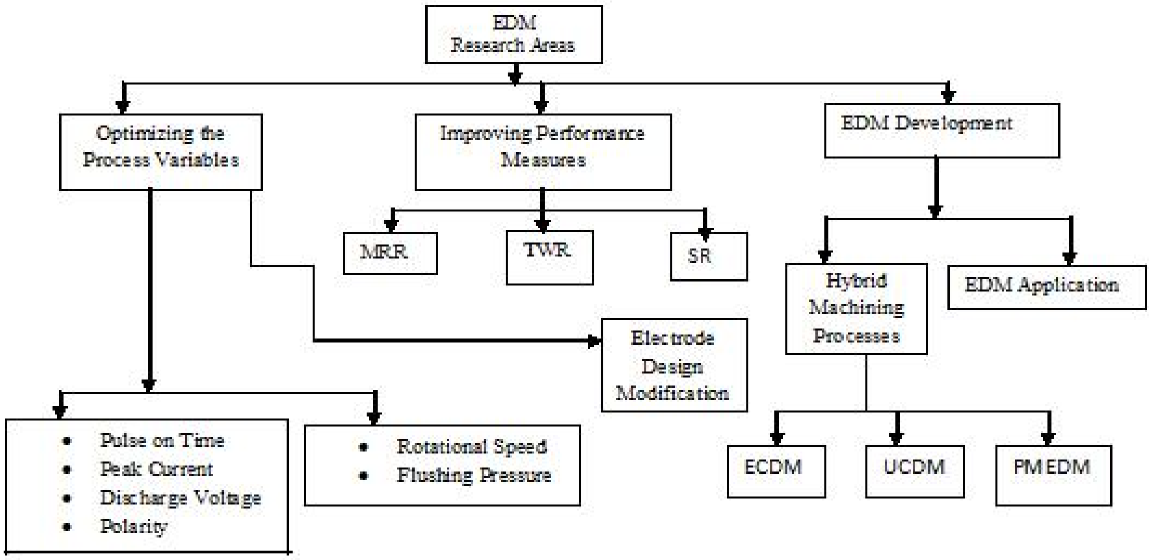


Figure 1.3 Classification of EDM research [57]

1.7.1 Discharge Voltage

Discharge voltage in the EDM is related to the spark gap and breakdown strength of the dielectric. If we set the voltage to a high value then the gap will increase, increasing the gap will improve the flushing conditions and helps to stabilize the cut. The open circuit voltage also have an impact to the system, as we increase the open circuit voltage tool wear rate (TWR) and surface roughness increases because the field strength increases.

1.7.2 Electrode Polarity

Polarity means the electric condition determining the direction of the current flow relative to the electrode. The polarity of the electrode can be either positive or negative depending on the application. Some electrodes give better results when the polarity is changed. There are two types of polarity namely:-

- Straight or normal polarity

- Reverse polarity

Straight or normal polarity is that in which the tool is positive and the work piece is negative, while in reverse polarity, tool is negative and the work piece is positive. Polarity can affect processing speed, finish, wear and stability of the EDM operation. It has been proved that MRR is more when the tool electrodes are connected at positive polarity (+) than at negative terminal (-) [55].

1.7.3 Pulse on Time (T_{ON})

Pulse on time is the time period during which the current is allowed to circulate through the electrode towards the work material within a short gap known as spark gap . Pulse on time is also referred as pulse duration. Metal removal is directly proportional to the amount of energy applied during the on-time [57]. The energy is controlled by the peak current and the length of the pulse on-time. The resulting crater will be deeper and broader produced by longer pulse on time than a crater produced by a shorter pulse on time. When the pulses with small on time are used, material removal by electron bombardment is predominant due to higher response rate of less massive electrons. However, when the longer pulses are used, energy sharing by positive ions is predominant and material removal rate decreases at constant current. When the electrode polarities are reversed, longer pulses are found to produce higher MRR.

1.7.4 Pulse off Time (T_{OFF})

The “pulse off time” is the time during which re-ionization of the dielectric takes place. The more is the off time, the greater will be the machining time. The cycle is completed when sufficient off-time is allowed before the start of the next cycle. Pulse off-time will affect the speed and stability of the cut. If the off-time is kept shorter, then faster will be the machining operation. 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 deionised. This will cause the next spark to be unstable.

1.7.5 Peak Current

This is the amount of power used in discharge machining, measured in units of amperage, and is the most important parameter of EDM. During each pulse on-time, the current increases until it reaches a pre-set level, which is expressed as the peak current. An increase in current, results in increased MRR as well as increased surface roughness (SR) and tool wear rate (TWR).

1.7.6 Electrode Gap (Spark Gap)

It is the distance between the electrode and the part during the process of EDM. To obtain good performance and gap stability a suitable gap should be maintained. It should neither be less nor more than the desirable [57].

1.7.7 Dielectric Fluid

For using a dielectric fluid in EDM process it is essential that they should have following characteristics:

- Remain electrically non-conducting until the required breakdown voltage has been reached.
- Breakdown electrically in the shortest possible time once the breakdown voltage has been reached.
- Rapidly quench the spark or deionise the spark or spark gap after the discharges have occurred.
- Provide an effective cooling medium.
- Deionise the gap immediately after the spark has occurred.
- Have good degree of fluidity.
- Should be cheap and easily available.

1.7.8 Tool Electrode

The EDM is basically a copying process and therefore the shape and accuracy of the machined part would largely depend upon the shape and accuracy of the cutting tool electrode. Metals with a high melting-point and good electrically conductivity is usually chosen as tool materials for EDM. They should be cheap and readily shaped by conventional methods.

Table.1 Selection of electrode material [61]

S.No.	Material	Wear Ratio	MRR	Fabrication	Cost	Applications
1.	Copper	Low	High on rough range	Easy	High	On all metals
2.	Brass	High	High only on	Easy	Low	On all metals

			finishing range			
3.	Tungsten	Lowest	Low	Difficult	High	Small holes are drilled
4.	Tungsten Copper Alloy	Low	Low	Difficult	High	Used higher accuracy work
5.	Cast Iron	Low	Low	Easy	Low	Used on few materials
6.	Steel	High	Low	Easy	Low	Used for finishing work
7.	Zinc based Alloy	High	High on rough range	Easy die casted	High	On all metals.
8.	Copper Graphite	Low	High	Difficult	High	On all metals.

1.7.9 Types of Flushing

Flushing is defined as the correct circulation of the dielectric fluid between electrode tool and work piece during operation. A dielectric in EDM must have a basic characteristic of high dielectric strength and quick recoveries after breakdown also have an effective quenching and flushing ability. In order to obtain highest machining efficiency, suitable flushing conditions are necessary. The different Flushing Techniques are:-Injection Flushing, Suction Flushing, Side Flushing, and Flushing by Dielectric Pumping [15].

1.8 EDM Surface Layers

The examination of a section of a surface layer produced by EDM (Figure: 1.4) reveals that there is a top white layer which crystallizes from liquid cooled at high speed. The death of the top melted zone depends on the pulse energy and duration. Below the top layer is a chemically affected layer with changes in the average chemical composition and possible phase changes. After this, there is a plastically deformed zone with micro and macro strains characterized by the presence of twinning, slip and phase changes.

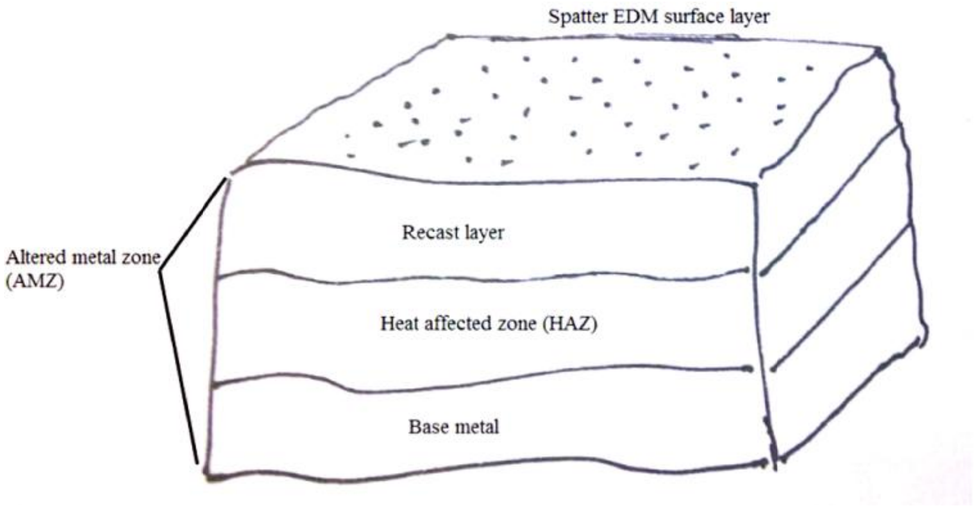


Figure: 1.4 Surface Layers after electrical discharge machining [15]

1.9 Organization of Thesis

Chapter 1 covers brief introduction to non-traditional machining, principle of electric discharge machining, explanation of powder mixed EDM and its various process parameters.

Chapter 2 presents an available literature on EDM process. The available literature has been categorized in different categories according to their applications. Summary of literature and gap in literature is also discussed.

Chapter 3 presents the methodology in brief which is being adopted. The detailed explanation of Taguchi and ANOVA is given. Objective and work plan is also discussed. The details of the machine used and workpiece used are also explained.

Chapter 4 presents the analysis and results of MRR. Results after the Analysis of Variance (ANOVA) and Taguchi Signal-to-Noise ratio are outlined in this chapter. Main effect plot and interaction plots for MRR are discussed in this chapter. Optimal design conditions have been discussed.

Chapter 5 presents the analysis and results of TWR. Results after the Analysis of Variance (ANOVA) and Taguchi Signal-to-Noise ratio are outlined in this chapter. Main effect plot and interaction plots for TWR are discussed in this chapter. Optimal design conditions have been discussed.

Chapter 6 presents the analysis and results of WR. Results after the Analysis of Variance (ANOVA) and Taguchi Signal-to-Noise ratio are outlined in this chapter. Main effect plot and interaction plots for WR are discussed in this chapter. Optimal design conditions have been discussed.

Chapter 7 presents the analysis and results of Geometric Accuracy. In this experiment, the profile or geometric accuracy have been studied using a tool with different front angle such as 45°, 90° and 135° under various parameters such as current, dielectric, powder concentration, pulse on time, powder on different materials. The angle generated on the workpiece is measured to evaluate the accuracy of the profile produced.

Chapter 8 presents the analysis of Surface Roughness. Surface Roughness is a very important parameter in terms of quality of the material.

Chapter 9 presents the analysis of surface properties, XRD and microstructure analysis which is used to understand the form and amount of deposition on the surface of the workpiece material.

Chapter 10 presents the results, conclusions and recommendations from the experimental work.

CHAPTER 2

LITERATURE REVIEW

2.1 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, dimensional accuracy along with hardness, roughness of the machined surface. The literature available on EDM is given below.

2.2 Effects of PMEDM

Many researchers have worked on effects of Powder Mixed EDM. Give below is the work of some of the researchers:-

Kansal et al. [4] discussed about Powder mixed electric discharge machining (PMEDM). In PMEDM, the electrically conductive powder is mixed in the dielectric of EDM, which reduces the insulating strength of the dielectric fluid and increases the spark gap between the tool and workpiece. As a result, the process becomes more stable, thereby, improving the material removal rate (MRR) and surface finish. Moreover, the surface develops high resistance to corrosion and abrasion. The paper presented a tutorial introduction, comprehensive history and review of research work carried out in the area of PMEDM. The machining mechanism, current issues, applications and observations were also discussed.

Kumar and Batra [5] investigated the response of three die steel materials(OHNS,D2,H13) to surface modification by EDM method with tungsten powder mixed in the dielectric medium. Peak current, pulse on-time and pulse off- time were taken as variable factors and micro-hardness of the machined surface was taken as the response parameter. Improvement of more than 100% in micro-hardness was found in case of all the three die steels. Machining parameters for the best value of micro-hardness for each work material were found to be the same. Favourable machining conditions for material transfer by EDM were found out to be low discharge current (less than 5A), shorter pulse on time (less than 10µs), longer pulse off time (more than 50µs) and negative polarity of tool electrode. Peak current was found to be most significant factor for phenomenon of surface modification.

Pecas and Henriques [6] investigated the influence of silicon powder-mixed dielectric on conventional electrical discharge machining. The paper presented a new 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 of AISI H-13 was assessed through quality surface indicators and process time measurements, over a set of different process parameters as peak current, duty cycle, polarity. The results showed a positive influence of the silicon powder in the reduction of the operating time, required to achieve a specific surface quality, and a decrease in surface roughness, allowing the generation of mirror-like surfaces.

Based on the experimental results, a set of conclusions were 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 between 0.09 µm for 1 cm^2 and 0.57 µm for 64 cm^2 copper electrode area. The surface roughness levels achieved are higher than the ones found in the literature as well as the electrode area influence. 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.

Singh [7] investigated the investigation on improvement of material properties & parametric optimization of MRR, TWR & Surface Roughness using powder mixed dielectric in EDM process. The objective was to study the effect of Aluminium & Graphite into Kerosene & Transformer Oil using different input parameters, namely, current, workpiece material, electrode material, dielectric medium, pulse on time, pulse off time and powder and some their interactions on the MRR, TWR, micro-hardness and surface roughness of HCHCr, EN-31& H-11 Die Steel using Cu, W-Cu electrodes. The assignment of factors was carried out using statistical software MINITAB. L_{27} which can accommodate a combination of 2-level and 3-level factors was used for conduct of experiments to measures the response values. The effect of various input parameters on output responses had been analyzed using Analysis of Variance (ANOVA). Deposition of the powder material either in pure form or in compound form was also studied. Main effect plot and interaction plot for significant factors and S/N ratio have been used to determine the optimal design for each output response. It was found that MRR and TWR were mainly affected by current and powder. Using graphite powder MRR was found to get decreased and hardness gets increased. Surface Roughness gets affected by current and pulse on time. Dielectric medium is least effective in surface roughness and micro hardness.

Sahai [8] investigated the mathematical modelling of material removal rate & hardness in electric discharge machining by DOE approach. Materials namely EN-24, EN-19, EN-353 were considered for study. Other parameters are peak current, pulse-on time, gap voltage & Performance Measures as MRR & Hardness. In order to attain target and optimum results, TAGUCHI method is employed. The appropriate orthogonal array has been selected as per number and there levels to performs minimum experimentation. The optimum value has been determined with the help of main effect plot and ANOVA table to find out optimum value. But ANOVA table was not supporting any parameter but it was proved that how machining of batch production can be improved. With help of MINITAB software mathematical modelling was found that was acceptable to experimental data also with help of fuzzy logic. The optimum value had been determined which is suitable for both MRR and hardness.

Sood [9] investigated the effect of powder mixed dielectric on Material removal rate, Tool wear rate and Surface properties in Electric Discharge Machining. EN31 die steel with copper electrode was considered. 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 L_{27} 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.

The results indicated that 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 was concluded and suggested to use graphite as an additive for PMEDM in comparison to that of copper.

Kumar et al. [10] reviewed the recent developments in the AEDM (Additives mixed EDM).The authors discovered that this machine is used at industry at a very slow pace because its fundamental issues including machining mechanisms are still not well understood. Additive powder characteristics (type, shape, size, concentrations, number of particles, and thermal properties) significantly affect process efficiency and surface characteristics of machined surfaces. So, thermo physical properties of additive particles deserve thorough investigations. Further, powder characteristics (type, shape, size concentration, etc.) also need thorough study for the optimization of process performance.

Singh [11] analysed the effects of Copper powder on high carbon high chromium, hot die steel, EN 31 with graphite and tungsten-copper electrode in kerosene oil & EDM oil. Effect of different input parameters like current, work piece material, electrode material, dielectric, pulse on and pulse off time & powder & their interactions on MRR,Tool,microhardness & SR were also studied. The assignment of factors was carried out using statistical software MINITAB. L_{27} which can accommodate a combination of 2-level and 3-level factors was used for conduct of experiments to measures response values. The effect of various input parameters on output responses had been analyzed using Analysis of Variance (ANOVA). Main effect plot and interaction plot for significant factors and S/N ratio have been used to determine the optimal design for each output response. It was found that MRR and TWR were mainly affected by current and powder. Using graphite powder MRR was found to get decreased and hardness gets increased. Surface Roughness was affected by current and pulse on time. Dielectric medium was least effective in surface roughness and micro hardness.

Singh et al. [12] investigated the influence of electrical parameters in powder mixed electric discharge machining of Hastelloy. PMEDM is a complex machining process which is controlled by number of machining parameters. Each machining parameter has its own influence on performance of the process. The objective was to analyze the effect of electrical parameters on the performance of this process. Peak current, gap voltage, pulse-on time and duty cycle are taken as machining parameters. Material removal rate, tool wear rate, % wear ratio and surface roughness were taken as response parameters to measure process performance. The experimental investigations were carried out using copper electrode & Al powder into EDM oil. Nineteen experiments are performed on hastelloy. Variations of response parameters were plotted against input machining parameters. The study indicated that all the input machining parameters strongly affect the machining performance of hastelloy. Higher peak current is desirable factor to yield more material erosion rate but it has adverse effect on surface finish of newly machined surfaces. Wear ratio decreases at higher peak currents and decreases at smaller gap voltage.

Abrol [13] investigated the effect of Chromium powder mixing into the dielectric fluid of EDM on machining characteristics of AISI D2 die steel had been studied. Four process parameters; namely peak current, pulse-on time, pulse-off time, concentration of powder have been considered. The process performance was measured in terms of material removal rate (MRR), tool wear rate (TWR) and surface roughness (SR). The experimental investigations were carried out using Copper electrode. The design of experiment had been undertaken using the Taguchi Methodology L_{27} Orthogonal Array. The ANOVA analysis was used for investigating the percentage contribution of peak current, pulse-on time, pulse-off time and concentration of powder towards maximizing of response measures by plotting the graphs against input machining parameters & Variations of response parameters. With the increase in current, MRR and TWR increase. Surface roughness was mainly affected by the pulse-off time. Surface Roughness is higher with the increase in pulse-off time.

Pecas and Henriques [14] investigated the electrical discharge machining using simple and powder-mixed dielectric, the effect of the electrode area in the surface roughness and topography. The objective was to acquire deep knowledge on EDM technology with silicon powder mixed Castrol SE Fluid 180 dielectric on AISI H-13 steel and to compare its performance to the conventional EDM when dealing with the generation of high-quality surfaces. In particular the analysis of the effect of the electrode area in the surface quality measured by the surface roughness and craters morphology was carried out for both technologies. The results achieved evidenced a linear relationship between the electrode area and the surface quality measures as well as a significant performance improvement when the powder mixed dielectric is used. Electrolytic Cu with peak current, duty cycle, polarity of electrode is used as process parameters. The result showed that the use of Powder Mixed-EDM conditions promotes the reduction of surface roughness, crater diameter, crater depth and the white-layer thickness. It was found that the sensitivity of the surface quality measures to the electrode area is smaller when mixed-power dielectric is used. Also, powder mixed dielectric significantly reduces surface heterogeneity contributing to increase process robustness. So, it contributes for the performance of the EDM process particularly when large electrode areas are involved and when a high-quality surface is a requirement.

Kumar [15] investigated the effect of Input Parameters namely current, work piece material(HDS, HCHCr, AISI 1045), dielectric, Pulse on time, powder concentration & powder(Silicon, Graphite and Tungsten) on TWR, MRR, micro hardness, microstructure & surface roughness. Measurement of overcut size & profile/geometry accuracy had been studied, front angle of tool (Cu) as 60°, 90°, 120°. Deposition of powder material either in pure form or in compound form was also studied. Optimization of pressure parameter had been studied.

Bhattacharya et al .[16] proposed a surface modification technique for HCHCr, EN 31 and HDS (Hot Die Steels) using PMEDM .It was found that micro hardness was majorly affected by current.

Kumar [17] carried out experimental investigation on the phenomenon of surface modification in three die steels (OHNS type2,HCHCr,H13)during EDM process using four different tool electrodes (cooper, graphite, copper-tungsten, Inconel)and then using four powders(graphite, manganese, silicon, tungsten) suspended in the dielectric medium. Peak current comes out to be most contributing factor followed by pulse on time and pulse off time in all the factors. Improvement in micro-hardness was also noticed in all cases. Copper-tungsten resulted in best combination of micro-hardness and surface roughness.

Batish et al. [18] investigated the material transfer from the powder suspended in dielectric, electrode and dielectric material for enhancing the surface properties measured in terms of micro hardness using PMEDM. Two kinds of die steels namely H11 and H13 were used for study. Powder materials used were Al, Cu, Gr, W. It was found that pulse on time increases with increase in micro-hardness while pulse off time has little influence on increase in micro-hardness.

Kumar [19] carried out experimental investigation on the Powder Mixed Electric Discharge Machining. Aluminium Oxide and Silicon Carbide were the powders used in machining. Machining Parameters namely Dielectric, Peak Current, Powder concentration, Pulse duration were changed to explore their effect on machining parameters namely MRR (Material Removal Rate), TWR (Tool Wear Rate), SR (Surface Roughness), Hardness and Micro-structure.MRR was found maximum in straight polarity as compared to reverse polarity.TWR got highest value in case of Silicon Carbide.

Kansal et al. [20] described an investigation into the optimization of EDM processes when silicon powder is suspended in dielectric fluid of EDM. Peak Current, Pulse duration, Duty cycle, powder concentration were considered as Input parameters while MRR and SR were considered as output parameters. Taguchi's parameter design approach (L_9) was used to obtain the optimal setting. The experimental results indicated significant improved performance of PMEDM over EDM.

Singh and Bhardwaj [21] reviewed the research trends in EDM in water and EDM with powder additives. In each topic, the development of the methods for the last 25 years was discussed & noticed much work in PMEDM rather than by using water as dielectric fluid. EDM in water was introduced for safe and conducive working environment; EDM with powder additives is concerning more on increasing SQ, MRR and tool wear using dielectric oil. EDM modelling was introduced to predict the output parameters which can lead towards the development of precise and accurate EDM performance. For each and every method introduced and employed in EDM process, the objectives were the same: to enhance the capability of machining performance, to get better output product, to develop technique to machine new materials and to have better working conditions.

Singh et al. [22] studied the effect of aluminium powder mixed in the dielectric fluid of Electric Discharge Machining on the machining characteristics of Hastelloy. Powder concentration and powder grain size were taken as Input parameters while Material Removal Rate (MRR), Tool Wear Rate (TWR), %age Wear Rate, Surface Roughness were taken as Output Parameters. The results showed that addition of aluminium powder increases MRR decreases TWR and improves surface finish of Hastelloy.

Jeswani [23] investigated the effect of addition of Graphite Powder to Dielectric fluid (Kerosene). Experimental results revealed that the addition of about 4g of fine grain powder per litre of kerosene increases the MRR by 60% and decreases TWR by 15%.

Kumar & Singh [24] investigated the surface properties of OHNS die steel after electrical discharge machining with manganese powder mixed in dielectric. Results showed that micro hardness got increased by 73% and no micro cracks were found on machined surface.

2.3 Effects of Workpiece Material

Many researchers have worked on effects of using different types of workpiece materials. Give below is the work of some of the researchers:-

Senthilkumar and Omprakash [25] found that Machining of hard materials such as metal matrix composites (Al/TiC) to a high degree of accuracy and surface finish is difficult. The objective of the work was to investigate the effect of current, Pulse On-Time and flushing pressure on MRR, TWR during EDM of as-sintered Al-MMC with 5% and 2.5% TiC reinforcement. Copper tool with kerosene as dielectric were used. L_{18} orthogonal array was used to perform experimentation. ANOVA was also performed to validate the experimental work.MRR and TWR were found influenced by discharge current. An attempt was also made in the present work to study the effect of TiC particle addition on the EWR.

Dhar et al. **[26]** analysed that Aluminium matrix composites (AMC) are hard to machine due to the presence of hard and brittle ceramic reinforcements. The author evaluates the effect of current, pulse-on time and air gap voltage on MRR, TWR, radial over cut on electric discharge machining of Al–4Cu–6Si alloy–10 wt. % SiCp composites. L_{27} orthogonal array was used to perform experimentation. ANOVA was performed to verify the fit and adequacy of the developed mathematical models. A mathematical model was also developed to predict the output parameters within operating region.

Singh et al. [27] found that the use of unconventional machining techniques in shaping aluminium metal matrix composites (Al-MMC) had generated considerable interest as the manufacturing of complicated die contours in these hard materials to a high degree of accuracy and surface finish was difficult.EDM is an important process for machining difficult-to-machine materials. The author investigated the effect of current, Pulse On-time and flushing pressure on MRR, TWR, taper, radial overcut and surface roughness on machining as-cast Al-MMC with 10% SiCp reinforcement.

Mohan et al. [28] analysed the effect of EDM parameters namely current, polarity, electrode material, pulse duration and rotation of electrode on MRR, TWR and SR of Al-SiC MMC with 20-25 vol% SiC. Irrespective of the electrode material, polarity of the electrode and vol % of SiC, MRR increases with increase in discharge current and for a specified current it decreased with increase in pulse duration. Increase in volume percentage of SiC had an inverse effect on MRR, positive effect on TWR and Surface finish. Increasing the speed of rotating electrode resulted in a positive effect with MRR, TWR and better SR than at stationary. Optimization of parameters was also done.

Saheb [29] tried to made to develop aluminium based silicon carbide particulate MMCs, graphite particulate MMCs with an objective to develop a conventional low cost method of producing MMCs and to obtain homogenous dispersion of ceramic material. Experiments were conducted by varying weight fraction of SiC, graphite and alumina (5%, 10%, 15%, 20%, 25%, and 30%), while graphite weight fraction 2%, 4%, 6%, 8% and 10% keep all other parameters constant. The results indicated that the 'developed method' is quite successful to obtain uniform dispersion of reinforcement in the matrix. An increasing of hardness and with increase in weight percentage of ceramic materials was also observed. The best results (maximum hardness) were obtained at 25 % weight fraction of SiC and at 4% weight fraction of graphite.

Suresha and Sridhara [32] investigated the friction characteristics of aluminium silicon carbide graphite hybrid composite and found that friction coefficient is influenced by sliding speed as well as load. Hardness of the component was found to decrease with increase in %age reinforcement

Hung et al. [30] investigated the feasibility of applying EDM process for cast aluminium MMCs reinforced with silicon carbide particles (SiCp). Effect of process parameters like voltage, current, pulse on time, and pulse off time on metal removal rate, re-cast layer, and surface finish was checked. It was found that the SiC particles shield and protect the aluminium matrix from being vaporized, thus reduces the metal removal rate.

Kathiresan and Sornakumar [31] developed aluminium alloy-silicon carbide composites using a new combination of vortex method or stir casting and pressure die casting technique. Electrical Discharge Machining (EDM) studies were conducted on the aluminium alloy-silicon carbide composite work piece using a copper electrode in an Electrical Discharge Machine. The Material Removal Rate (MRR) and surface roughness of the work piece increases with an increase in the current. The MRR decreases with increase in the percent weight of silicon carbide. The surface finish of the machined work piece improved with percent weight of silicon carbide.

Krishnamurthy et al. [33] presented the result of an experimental investigation on the comparative machinability of aluminium-silicon carbide composites and aluminium-graphite-silicon carbide hybrid composites during turning using carbide tool inserts. The influence of machining parameters viz. cutting speed, feed and depth of cut on the resultant force has been analysed statistically. It was established that hybrid composites have better machinability when compared to aluminium-silicon carbide composites.

Marafona et al. [34] tried to show the influence of hardness of alloy steel on MRR and Surface Roughness. The results explained that electrical discharge machining process is not only influenced by the thermal properties of the workpiece but also by its hardness.

George et al. [35] investigated about determining the optimal setting of the process parameters on the electro-discharge machining (EDM) machine while machining carbon–carbon composites. The parameters considered were pulse current, gap voltage and pulse-on-time; whereas the responses are electrode wear rate (EWR) and material removal rate (MRR). It was found that the electrode wear rate reduces substantially, within the region of experimentation, if the parameters were set at their lowest values, while the parameters set at their highest values increase the MRR drastically.

Chawla and Ganesh [36] investigated that the fatigue resistance of particulate metal matrix composite depends on a variety of factors including reinforcement particle volume fraction, particle size, matrix microstructure and the presence of inclusions or defects that arise from processing. The workpiece chosen for study are 2080/SiC_p composite and 2080 Al alloy. The goal of this research was to obtain a fundamental understanding of fatigue crack growth behaviour and evolution of microstructure during fatigue.

Pichai and Muttamara [37] found that EDM is the main process to make tungsten carbide (WC-Co) moulds and dies. Normally, the EDM process generates micro cracks on the surface of the work piece. Consequently, the life time of the moulds or tools can be shortened because of defects in the product parts. So, the researcher investigated the optimal process parameters to minimize the micro crack density (Cr.S.Dn), electrode wear ratio (EWR) and maximize material removal on 90 WC-10 Co Composite. To reduce the number of experiments, the Taguchi design using an L_9 orthogonal array was used. Analysis of variance (ANOVA) and signal-to-noise (S/N) ratio were performed and calculated, respectively. The important control parameters were the following: discharge current, off time, and open-circuit voltage. The experimental work pieces were composed of tungsten carbide, and graphite electrodes were used. Using the Taguchi approach, the significant factors of MRR, EWR, Cr.S.Dn and their associated levels on each response were determined by ANOVA analyses. The discharge current parameters mainly affected the MRR, EWR and Cr.S.Dn.

Rao et al. [38] had carried out study on the influence of four design factors: current, open-circuit voltage, duty cycle and servo over material removal rate, tool wear rate, surface roughness and hardness on the die-sinking electrical discharge machining of AISI 304 stainless steel. L_{28} orthogonal array was used to reduce the number of experiments. ANOVA was used to find the contribution of all the possible effects. The most significant and interaction factor effects were determined from Pareto charts and Normal Probability Plots.

Iqbal and Khan [39] aimed to optimize the process parameters during EDM milling of stainless steel by using copper electrode. The selected input parameters used for the study are voltage, rotational speed of the electrode and feed rate while the responses are material removal rate (MRR), electrode wear ratio (EWR) and surface roughness (Ra). Optimization of process parameters concerned with maximizing MRR, minimizing EWR and producing surface finish as smooth as possible.

Reza et.al. [40] tried the optimization of Electrical Discharge Machining (EDM) Injection flushing type control parameters on multi-performance optimization Method using Grey Relational Analysis Method (GRA). The experimental control parameters were being optimized according to their various machining characteristics namely material removal rate (MRR), electrode wear ratio (EWR) and surface roughness (SR) using copper as the tool and AISI 304 stainless steel as the workpiece. The machining parameters selected are polarity, pulse on duration, discharge current, discharge voltage, machining depth, machining diameter and dielectric liquid pressure. Results showed that machining performance was improved effectively using this approach. The predicted responses at optimum parameter levels were in good agreement with the results of confirmation experiments conducted for verification tests.

Choudhary et al.[41] conducted the investigations on the machining of EN-31 die steel with different electrode materials (copper, brass and graphite) with electrical discharge machining (EDM) process to present the analysis and evaluation of heat affected zones (HAZ) of the workpiece surfaces machined using different tool electrodes by EDM. The effect of various important EDM parameters such as pulse duration, peak current and discharge gap voltage has been investigated to yield the responses in terms of material removal rate (MRR) and surface roughness (SR). Experimental results indicated that copper as a tool electrode shows a good response towards MRR, whereas brass gives superior surface finish as compared to other tool electrodes. From the micro structural analysis study, it was observed that heat affected zone was much deeper in the specimen machined by graphite electrode as compared to other tool electrodes.

Nipanikar [42] conducted the cutting of D3 Steel material using electro discharge machining (EDM) with a copper electrode by using Taguchi methodology. The Taguchi method was used to formulate the experimental layout, to analyse the effect of each parameter on the machining characteristics, and to predict the optimal choice for each EDM parameter such as peak current, gap voltage, duty cycle and pulse on time. It was found that these parameters had a significant influence on machining characteristic such as material removal rate (MRR), electrode wear rate (EWR), radial overcut (ROC). The analysis using Taguchi method revealed that, in general the peak current significantly affects the MRR, EWR and ROC.

Pradhan and Biswas [43] used Response Surface Methodology (RSM) to investigate the effect of four controllable input variables namely: discharge current, pulse duration, pulse off time and applied voltage on Surface Roughness (SR) of Electrical Discharge Machined surface. To study the proposed second-order polynomial model for SR, a Central Composite Design (CCD) was used to estimate the model coefficients of the four input factors, which are alleged to influence the SR in Electrical Discharge Machining (EDM) process. Experiments were conducted on AISI D2 tool steel with copper electrode. The response was modeled using RSM on experimental data. The significant coefficients were obtained by performing Analysis of Variance (ANOVA). It was found that discharge current, pulse duration, and pulse off time and few of their interactions have significant effect on the SR.

Ghose et al. [44] found that conventional machining of aluminium foams is a difficult task because of the fact that their cells and cell edges are damaged and/or collapsed during the machining processes and there by the original properties deteriorated. This problem can be overcome to a certain extent by using EDM Process. The paper deals with identifying the various control parameters responsible for effective machining of aluminium foam. Taguchi-Fuzzy Logic based technique was used for parameter design of performance characteristics to determine optimal machining parameters for maximum Material Removal Rate (MRR) and minimum Tool Wear Rate (TWR) in EDM. Taguchi-fuzzy based mapping of MRR and TWR with productivity revealed that in order to achieve higher productivity while machining aluminium foam, the two parameters, pulse current and pulse-On time are required to be set high in combination with the low setting of duty cycle.

2.4 Effects of Tool Material

Many researchers have worked on effects of different materials on the workpiece of tool. Give below is the work of some of the researchers:-

Patel et al. [45] conducted experiments on Mild steel with copper, brass and graphite as tool electrodes with kerosene oil as dielectric fluid. The data compiled during experimentation was used to yield responses in respect of MRR and SR. Mode of heat affected zone (HAZ) was also studied which alternatively affects structure of machined workpiece and hence tool life. All three specimens machined by different electrodes showed different patterns of HAZ. For high discharge current, Al and Cu electrode show maximum MRR whereas brass gives good surface finish and normal MRR.

Tomadi et al. [46] studied the influence of operating parameters of tungsten carbide namely peak current, supply voltage, pulse on time and pulse off time on machining characteristics such as surface control, MRR and electrode wear. Optimization of machining conditions was also done using STATISTICA software. This was done by using the Design of Experiments (DOE) technique and ANOVA analysis. Better machining performance were obtained with electrode as cathode and workpiece as anode.

Haron et al. [47] studied that EDM is a process of utilizing the removal phenomenon of electrical-discharge in dielectric; therefore, the electrode plays an important role, which affects the material removal rate and the tool wear rate. So, the machining characteristics were investigated when machining XW42 tool steel at two current settings (3A and 6 A), three diameter sizes (10, 15 and

20mm) and kerosene as the dielectric. The results showed that the material removal rate is higher and the relative electrode wear ratio is lower with copper electrode than graphite electrode. The increase in the current and electrode diameter reduced tool wear rate as well as the material removal rate.

Iosub et al. [48] investigated the effect of tool diameter and pulse-on time (ton) on the tool wear rate, material removal rate and surface integrity of silicon carbide hybrid aluminium matrix composites. Aluminium metal matrix hybrid composite with 7% silicon carbide (SiC) was drilled by using steel electrode tool with two different diameters. Positive polarity was maintained and water – soluble dielectric fluid VITOL KS was used. It was found that by increasing the pulse duration the electrode wear and machining speed increase. In case of drilling deep holes with small diameters, the electrode tool wear was more pronounced and the machining speed got decreased significantly.

Ojha et al. [49] carried out Parametric Optimization for material removal rate (MRR) and tool wear rate (TWR) study on the powder mixed electrical discharge machining (PMEDM) of EN-8 steel using Chromium Powder Mixed Dielectric and Triangular Shaped Electrodes (with constant cross sectional area of 50 mm^2 and angles of 50°,90° and 130°). Response surface methodology (RSM) was used to plan and analyze the experiments. Average current, duty cycle, angle of electrode and concentration of chromium powder added into dielectric fluid of EDM were chosen as process parameters to study the PMEDM performance in terms of MRR and TWR. TWR was found decreasing with increase in tool angle. Most important parameters affecting selected performance measures were identified and effects of their variations were observed.

Dewangan [50] found out the effect of machining parameter such as discharge current, pulse on time and diameter of tool on AISI P20 material using U-shaped Copper tool with internal flushing. Experiments were conducted with the L_{18} orthogonal array based on the Taguchi method. The Signal-to-Noise ratios associated with the observed values in the experiments were determined by which factor is most affected by the Responses of Material Removal Rate (MRR), Tool Wear Rate (TWR) and over cut (OC).It was found in the results of MRR, discharge current was most influencing factor and then pulse duration time and the last was diameter of the tool. MRR increased with the discharge current. As the pulse duration extended, the MRR decreases monotonically. In the case of Tool wear rate, the most important factor was discharge current then pulse on time and after that diameter of tool. In the case of over cut the most important factor of discharge current then diameter of the tool and no effect on pulse on time.

Pellicer et al. [51] focused on investigating the influence of EDM parameters and electrode geometry on feature micro-accuracy in tool steel for mould fabrication purposes. A set of designed experiments with varying EDM process parameters such as pulsed current, open voltage, pulse time, and pulse pause time was carried out in H13 steel using differently shaped copper electrodes. Micro dimensional and geometrical accuracies were the measures of response. Artificial neural network and regression models were constructed to capture the influence of the process parameters on the geometrical feature quality such as flatness, depth, slope, width, and dimension variation between the entrance and the exit (DVEE).

Prajapati et al. [52] objective was to study the performance of different electrode Materials on EN-9 workpiece with EDM process. The electrode materials were graphite, copper and Brass. The important parameters were peak current, pulse on time, pulse off. A workpiece material was EN-9. The results showed that the Graphite electrode gives higher MRR than other two Electrodes. Brass electrode gives better surface finishing among three electrodes. Powder electrode gives the better MRR and high SR more than solid electrode.

Singh et al. [53] reported the results of an experimental investigation carried out to study the effects of machining parameters such as pulsed current on material removal rate, diameteral overcut, electrode wear and surface roughness in electric discharge machining of En-31 tool steel (IS designation: T105 Cr 1 Mn 60) hardened and tempered to 55 HRc. The work material was machined with copper, copper tungsten, brass and aluminium electrodes by varying the pulsed current at reverse polarity. Investigations indicated that the output parameters of EDM increase with the increase in pulsed current and the best machining rates are achieved with copper and aluminium electrodes.

Khan et al. [54] discussed the performance of die sinking EDM due to the shape configuration of the electrode. The effect of electrode shape on material removal rate (MRR), electrode wear rate (EWR), wear ratio (WR), and average surface roughness (R_a) was investigated for mild steel work material and copper electrode. The shapes of the electrodes were round, square, triangular, and diamond of constant cross-sectional area of 64 mm^2. Experiments were repeated for three current values of 2.5, 3.5, and 6.5 A. The highest MRR was found for round electrodes followed by square, triangular and diamond shaped electrodes. However, the highest EWR and WR were found for the diamond shaped electrodes. The minimum surface roughness was found for the round electrodes followed by square, triangular and diamond shaped electrodes. However, the influence of the shape of the electrodes on surface roughness was found to be insignificant.

2.5 Some Other Appreciable Factors

Many researchers have studied some other appreciable factors affecting EDM namely effect of energy duration, explanation of mechanism of material removal, mineral oil based dielectric and so on. All these types of factors are discussed below:-

Khatter[55] tried to optimize the experimental conditions for an effective energy distribution which is available in electric discharge machining for tungsten carbide. Input parameters were taken as peak current, pulse duration and polarity while output parameters were MRR, surface roughness, micro-hardness and microstructure.MRR and Surface Roughness values increased with increase in discharge current for all the three electrode materials namely Graphite, Copper-Tungsten, and Copper.

Ojha et al. [56] studied the previous work done by researchers in field of EDM for improving MRR and to bridge the gap between the untouched areas. So, it represent researches done on EDM relating to improvement in MRR along with some insight into mechanism of material removal.

Pandey and Singh [57] reviewed the state of the art technology of high -performance machining of advanced materials with detail explanation of EDM, Die Sinking EDM, WEDM, Micro-EDM, Dry EDM AND RDE-EDM (Rotary Disc Electrode- EDM), Hybrid EDM process.

Mahendran et al. [58] gave an overview about Micro-EDM and its parameters. Micro-EDM is an efficient machining process for the fabrication of a micro-metal hole with various advantages resulting from its characteristics of non-contact and thermal process. A pulse discharges occur in a small gap between the work piece and the electrode and at the same time removes the unwanted material from the parent metal through the process of melting and vaporization.

Zhang et al. [60] found that EDM causes a recast layer to form at the machined surface of the work-piece. The characteristics of the recast layer have a great relationship with the type of dielectric. The characteristics of the recast layer formed in W/O (Water in Oil which means 66 vol% of machine oil, 34 vol% of deionised water) emulsion were investigated by comparing them with those of the recast layer formed in kerosene and de-ionized water dielectric. It was found that the recast layer formed in W/O emulsion exhibited larger surface roughness, thickness and micro hardness compared with that formed in kerosene and de-ionized water. Both carbide and oxide were detected in the recast layer formed in W/O emulsion whereas only carbide was detected in the recast layer formed in kerosene.

Due to the higher super saturation of gases in the melted material, the recast layer formed in W/O emulsion was found to possess more micro-voids than that formed in kerosene and de-ionized water.

Saha [59] found that use of mineral oil based dielectric liquids is the major cause of environmental concerns associated with the EDM process. Dry EDM is an environment-friendly modification of the oil EDM process in which a gaseous medium replaces the liquid dielectric. So, an independent machining unit was designed and developed for implementing the dry EDM process on an existing oil EDM machine. The unit was designed to satisfy the basic requirements for dry EDM, i.e. high velocity gas flow through a rotating tubular tool. Parametric analyses were done by conducting a set of experiments using air as the dielectric medium. Effect of gap voltage, discharge current, pulse-on time, duty factor, air pressure and spindle speed on material removal rate (MRR) and surface finish (Ra) had been studied. Empirical models for MRR and R_a had been developed by conducting a designed experiment Optimization results were used for identifying the rough and finish machining conditions. For verification of the empirical models and the optimization results, focused experiments were conducted in the rough and finish machining regions. Finally, a comparison of the process performance in dry EDM and oil EDM was made. It was experimentally found that although the MRR is lower in dry EDM, surface finish and tool wear rate are much better than in oil EDM.

2.6 Summary of Literature Review

A lot of work has been done in the field of composites. From the above literature, it was found that Al-composites are of great interest of researchers. [27,28,10,15,30,31,55,32,33] have investigated the effect of various parameters like current, pulse on time on the variables like MRR,TWR,SR,EWR on the Al-MMC. Tool wear was found to be less at higher values of pulse current when negative polarity was used. It is recommended that for best values of MRR and Surface Finish, machining should be carried out with negative polarity at low values of pulse current and pulse on time [10].MRR increases with increase in current and pulse on time. Surface roughness increases with increase in current and pulse on time [27].Some researchers [28] found the effect of rotation of electrodes namely copper and of brass on Al-MMC. MRR was found that more when the electrodes were at positive polarity than at negative.

Some researchers [15, 45] even checked the effect of electrode material and its angle. [45] Investigated the effect on MRR and SR on mild steel specimen with copper, brass and graphite electrodes. Brass shows good response in surface finish as compared to other electrodes. [15] Observed that when the tool front angle is small then more variation occurs in sparking at different places between the tool and workpiece and thus the angle generated on the workpiece is less accurate.

Due to the large application of AISI 304, some researchers [40, 38, 39] have studied the effect of output variables like MRR, TWR on input parameters like Current, Pulse on time etc on AISI 304.

Some researchers [4, 5, 10, 7, 11, 15, 16, 24, 57] have studied the PMEDM. [4]has explained the concept of PMEDM in detail.[11] has studied the effect of using copper as powder while [5] has studied the effect of using Tungsten as powder. Peak current, pulse on time and pulse off time were taken as variable factors while micro hardness was taken as output parameter. Favourable machining conditions for material transfer are found to be low current(less than 5A), shorter pulse on time (less than 10 µs), longer pulse off time (more than 50 µs) and negative polarity of the tool electrode. Material transfer through additive powders suspended in the dielectric medium offer a viable route to modify the surface characteristics. There is a need to independently study the effect of various powder characteristics with important input process parameter on the phenomenon of surface modification and process capabilities. Thus, exploring the complicated interrelationship between different input parameters of processes and their optimization under such operational conditions will remain a key issue for further developments. [57] Found that for surface finish best results are obtained from Al and Graphite Powder particles having diameter less than 15µm and concentration ranging from 2 to 15 g/l.

Some researchers [59-60] found the effect of dielectric medium on various parameters. [60] Suggested Dry EDM process. [59] Discussed about the recast layer which is formed at the machined surface of the workpiece.

Some researchers [32, 35 and 41] studied the machining of elements like Tungsten carbide, carbon-carbon composites, EN 31 die steels. Some researchers [57, 58] discussed advanced versions of EDM like Micro-EDM, Wire EDM etc.

2.7 Gaps in Literature

It was concluded from the literature review that still there is need of work to be done on Powder Mixed Electric Discharge Machining (PMEDM) of composites and alloys .Composite materials and alloys are important engineering materials due to their outstanding mechanical properties. These composites and alloys are finding extensive applications in manufacturing industries. So, the workpiece materials proposed for study are: - MMC (Al/SiC), Al/Cu alloy, AISI 304.

Applications of MMC (Al/SiC): - It finds applications in automobiles, aerospace and military industries because of their attractive properties such as high strength to weight ratio, high wear resistance, high temperature stability etc. The addition of solid lubricants such as Graphite along with SiC particulates as hybrid reinforcements effectively improves the tribological properties. One of the advantages of this composite is that they are self lubricating materials containing graphite and yet their strength is enhanced by the presence of the SiC ceramic phase [33].

Applications of Al/Cu alloy: - The aluminium-copper alloys typically contain between 2 to 10% copper, with smaller additions of other elements. The copper provides substantial increases in strength and facilitates precipitation hardening. The introduction of copper to aluminium can also reduce ductility and corrosion resistance. The susceptibility to solidification cracking of aluminium-copper alloys is increased; consequently, some of these alloys can be the most challenging aluminium alloys to weld. These alloys include some of the highest strength heat treatable aluminium alloys. The most common applications for the 2xxx series alloys are aerospace, military vehicles and rocket fins.

Applications of AISI 304 alloy: - AISI 304 stainless steel material is having a wide range of applications in the industrial field: Chemical, Pharmaceutical, Cyrogenics, Food, Diary, Paper Industries. The important characteristics responsible for the commercial popularity of this material are its ability to resistance to corrosion and staining. Low maintenance, relatively low cost and familiar lustre make it an ideal base material for a host of commercial applications. AISI 304 is used in almost all industrial applications. The consumption of this stainless steel is about 50% of the total consumption of stainless steel in the world [38, 39].

2.8 Objective of the Present Work

The objective of the present work has been discussed below:

1) To study the effect of various input parameters like current, Powder material, Powder concentration, tool angle, Workpiece material, Dielectric Medium on output parameters like Material Removal Rate (MRR), Tool Wear Ratio (TWR),Wear Ratio (WR),surface roughness, geometric accuracy.

2) The experimentation work will be planned by applying DOE (Design of Experiments) approach.

3) Analysis of results obtained from the experimentation work will be done using the Statistical Techniques such as ANOVA (Analysis of Variance).

4) The optimization and verification of results will be done. Also the modelling of results will be done by applying the Regression Analysis.

5) The machined samples will be studied for the microstructure details using testing techniques.

CHAPTER 3

EXPERIMENTATION AND DESIGN OF STUDY

3.1 Design Factors Selection

3.1.1 Process parameters selection

A large number of input process parameters can be varied in the PMEDM 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. Current

c. Type of Powder

d. Pulse on-time

e. Pulse off-time

f. Powder Concentration

g. Electrode Material

h. Workpiece Material

i. Machining Time

j. Electrode Shape

k. Type of Dielectric

The effect of each of these parameters on EDM process is discussed in the literature review in detail. Out of these parameters, seven parameters have been investigated thoroughly in this research work. These seven parameters are

1. **Current (ampere)**
2. **Pulse on-time (μs)**
3. **Powder Material**
4. **Powder Concentration (gm/lit.)**

5. **Dielectric**
6. **Electrode Angle**
7. **Workpiece Material**

After the selection of process parameters & their levels, a design model was prepared and then the experimentation work was performed.

3.1.2 Response variable selection

The response variables selected in this study were MRR, TWR ,WR & Surface Roughness. These variables are defined as:

Material Removal Rate (MRR) is defined as the weight of material eroded from workpiece surface per unit time. It is measured as:

$$\text{MRR } (mm^3/\text{min.}) = \frac{weight\ difference\ of\ w/p\ (gm)}{Machining\ time(min.) \times density\ of\ workmaterial(\frac{gm}{mm^3})} \quad \text{(Equation 3.1)}$$

Tool Wear Rate (TWR) is defined as the weight of material eroded from tool electrode surface per unit time. It is measured as:

$$\text{TWR } (mm^3/\text{min.}) = \frac{\text{weight difference of electrode (gm)}}{\text{Machining time(min.)} \times \text{Density of electrode material}(\frac{gm}{mm^3})} \quad \text{(Equation 3.2)}$$

Wear Ratio is defined as the ratio of TWR and MRR and is measured as:

$$WR = \frac{TWR}{MRR} \quad \text{(Equation 3.3)}$$

Surface Roughness (R_a) is the arithmetic average roughness of the deviations of the roughness profile from the central line along the measurement.

$$\text{Surface Roughness } (R_a) = \frac{1}{L}\int_0^L |h(x)\ dx| \quad \text{(Equation 3.4)}$$

where h(x) is the value of roughness profile & L is evaluation length

3.1.3 Experimental Design

As the objective of this research work is to study the effect of powder mixed in the dielectric upon MRR, TWR 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) Three levels of concentration of powder in the dielectric one by one.

b) Three levels of current; because the non-linear behaviour of process parameters can only be studied if more than two levels of a parameter are used.

c) Three levels of pulse on-time.

d) Three levels of powder material.

e) Three levels of electrode front angle.

f) Three levels of workpiece material.

g) Two levels of dielectric fluid.

For conducting the experiments, it was decided to follow the Taguchi method of experimental design so that the effect of all the parameters could be studied with minimum possible number of experiments and an appropriate orthogonal array had to be selected after taking into consideration the above design variables and experiments were performed as per the set of experiments designed in the orthogonal array. Signal to Noise ratios were also calculated to analyze the effect of PMEDM more accurately.

Polarity was made 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.

The Taguchi method apparently has the following strengths:

1. Consistency in experimental design and analysis.

2. Reduction of time and cost of experiments.

3. Robustness of performance without removing the noise factors.

The whole procedure of Taguchi method is as under.

1. Establishment of objective functions.

2. Selection of factors and/or interactions to be evaluated.

3. Identifications of uncontrollable factors and test conditions.

4. Selection of number of levels for the controllable and uncontrollable factors.

5. Calculation total degree of freedom needed

6. Select the appropriate Orthogonal Array (OA).

7. Assignment of factors and/or interactions to columns.

8. Execution of experiments according to trial conditions in the array.

9. Analyze results.

10. Confirmation experiments

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

Table 3.1 Fixed Input Process Parameters

S.No.	**Machining Parameters**	**Constant Value**
1	Open circuit voltage	135 ± 5% Volts
2	Polarity	Straight(+ve)
3	Machining Time	06min
4	Pulse off time	85μs

3.1.4 Selection of Orthogonal Array & Parameter Assignment

In this experiment, there are six parameters at three levels and one parameter at two levels. The degree of freedom (DOF) of a three level parameter is 2 (number of levels-1) and similarly, for a two level parameter DOF is 1, hence total DOF for the experiment is 13. The DOF of the orthogonal array selected should be higher than that of total DOF of the experiment. So, the Orthogonal Array (OA) which can be used for this experimentation is L_{18}, which has 17 DOF assigned to its various columns. The additional four DOF were used to measure the random error.

Table 3.2 DOF allocated to various factor combinations

Interaction	Units	DOF	Levels		
			Level-1	Level-2	Level-3
Dielectric(A)	-	1	Kerosene	EDM oil	-
Workpiece Material(B)	-	2	AISI 304	Al/Cu ALLOY	Al/SiC MMC
Angle (C)	° (degrees)	2	45	90	135
Powder concentration (D)	gm/lit	2	10	15	20
Current (E)	Ampere	2	2	5	8
Pulse on-Time (F)	µ sec	2	10	50	100
Powder(G)	-	2	Si	Cu	Graphite
Total		13	-	-	-

Table 3.3 Standard L_{18} Orthogonal Array (Taguchi Design)

Trial No.	Dielectric	Workpiece	Angle	Concentration	Current	Pulse On Time	Powder
1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2
3	1	1	3	3	3	3	3
4	1	2	1	1	2	2	3
5	1	2	2	2	3	3	1
6	1	2	3	3	1	1	2
7	1	3	1	2	1	3	2
8	1	3	2	3	2	1	3
9	1	3	3	1	3	2	1

10	2	1	1	3	3	2	2
11	2	1	2	1	1	3	3
12	2	1	3	2	2	1	1
13	2	2	1	2	3	1	3
14	2	2	2	3	1	2	1
15	2	2	3	1	2	3	2
16	2	3	1	2	2	3	1
17	2	3	2	1	3	1	2
18	2	3	3	2	1	2	3

3.1.5 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.*
- Those which affect the variability in the response, the *Variability Control Factors (VCF).*

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:**

HB: S/N ratio = $-10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^{-2}\right]$ (Equation 3.5)

- **Lower the Better:**

LB: S/N ratio= $-10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^{2}\right]$ (Equation 3.6)

- **Nominal the Best:**

NB: S/N ratio = $10log_{10}\left[\frac{Y^{-2}}{S^2}\right]$ (Equation 3.7)

Where Y_i is the sample mean & S is the sample standard deviation of n observations in each trial. 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:

Table 3.4: Response Characteristics

Response Name	**Response Type**	**Units**
Material Removal Rate(MRR)	Higher the better	mm^3/min
Tool Wear Rate(TWR)	Lower the better	mm^3/min
Wear Ratio(WR)	Lower the better	-
Surface Roughness(R_a)	Lower the better	micron

3.2 Analysis of Results Using ANOVA

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 are 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.

The purpose of the statistical analysis of variance (ANOVA) is to investigate which design parameter significantly affects the material removal rate, tool wear rate & surface roughness. In my thesis ANOVA table is made with help of **MINITAB 16** Software.

Various formulas for ANOVA are:

Sum of square, SS = $\sum_{i=1}^{N} Y_i^2 - \frac{T^2}{N}$ (Equation 3.8)

DOF = Levels of Parameters-1 (Equation 3.9)

Variance = $\frac{SS}{DOF}$ (Equation 3.10)

F-test = $\frac{variation\ due\ to\ parameter}{Variation\ due\ to\ error}$ (Equation 3.11)

e-pooled = sum of SS due to error and SS of all insignificant factors (Equation 3.12)

$SS' = SS$ of significant factor – DOF of that factor × variation due to e _ pooled

(Equation 3.13)

C% = $\frac{SS'}{\text{Total SS}} \times 100$ (Equation 3.14)

If **F-critical > F-test**

Only then the factor is significant for the given conditions.

Where DOF = Degree of Freedom

F test = Fisher's test

C% = Contribution Factor

3.3 Description of the EDM Machine

The experiments have been conducted on the Electrical Discharge Machine model T-3822 (Figure 3.1) of Victory Electromech available at Thapar University, Patiala in the Machine Tool Lab. Many input parameters like discharge voltage, pulse on time, pulse off time, polarity, peak current, electrode gap and type of flushing can be varied in EDM process. Each factor has its own effect on the output parameters such as TWR, MRR, SR, hardness of the machined surface, geometry accuracy.

Special Mild Steel tank was used for conducting the experiments so that the suspended powder particles do not clog the filtering system. This tank of size 330 x 200 x 200 mm was made with 4 mm thick mild steel and had capacity of 9 litres. A stirrer rotating at 1400 rpm was used in the tank for proper mixing of the powder in the dielectric. Schematic diagram of set up is shown in Figure 3.2. The tank was installed in EDM machine as shown in Figure 3.3.

Figure 3.1 Electrical Discharge Machine [Courtesy by: NTM Lab, Thapar University,Patiala]

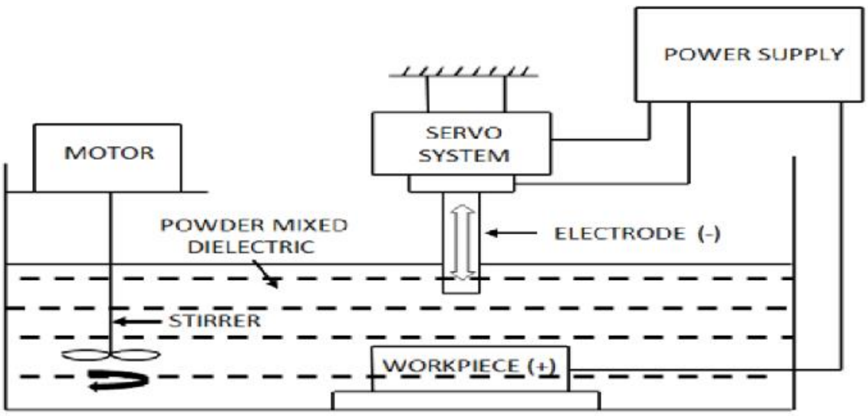


Figure 3.2 Schematic diagram of set up [7]

Figure 3.3 Dielectric Tank along with stirrer [Courtesy by: NTM Lab, Thapar University, Patiala]

3.4 Measuring and Test Equipment Used

Surface Roughness tests were conducted on most of the samples, produced after each of 18 trials. Also, MRR and TWR were measured using Weighting Machine. The details of important test equipment used in experimental study are given below:

3.4.1 Surface Roughness Tester

Surface Roughness was measured using the Perthometer; model M4Pi of Mahr, Germany. The equipment uses the stylus method of measurement, has profile resolution of 12 nm and measures roughness up to 100µm.

3.4.2 Micro Hardness Tester

Micro hardness was measured on a computer interfaced Micro Hardness Tester, (model MVH-2) Metatech industries, Pune, India. The micro hardness measurement is dependent on the diameter of indentation on the samples. The indent formed in the pyramid shaped indenter was measured with Quantimet software using a load of 1kg for 20 seconds.

3.4.3 X-Ray Diffraction Machine

XRD analysis was carried out of some samples on X-Ray Diffraction Machine, (model ME 210 LA 2) of Rigaku corporation, Japan available at IIT, Roorkee. Scan speed of 5°/minute for each test was used.

3.4.4 Scanning Electron Microscope Machine

Microstructure was carried out of some selected samples on Scanning Electron Microscope (SEM), model JSM-6610 LV of Jeol, Japan available at IIT,Ropar. Its resolution in high vacuum mode is 3nm. Its maximum magnification range is 3, 00,000x. SEM of samples was carried out on three ranges, namely 200x, 500 x and 1000x.

3.4.5 Weighting Machine

Precision balance was used to measure the weight of the workpiece and tool. This machine capacity is 300gram and accuracy is 0.001 gram and Brand: SHINKO DENSSHI Co. Ltd, Japan. Model: DJ 300S.

3.4.6 Vernier Caliper

Vernier Caliper was used to measure the diameter and depth of cut. The Vernier caliper is of Mitutoyo and its least count is 0.02mm.

3.5 Test Results for Workpiece & Electrode

Three workpiece materials namely Aluminium-Silicon Carbide Composite(MMC), Aluminium – Copper alloy (ALLOY)and AISI 304 and three angles of electrode namely 45°,90° and 135° were used. Figure 3.4 and Figure 3.5 shows the workpiece before and after the experimentation. The angles of electrode are shown in Figure 3.6. The dimensions of workpiece used for MMC and ALLOY were 100 x 100 x 10 mm^3. The dimensions of the workpiece used for AISI 304 were 150 x 150 x 10 mm^3. Table 3.5 shows the chemical composition of workpiece material.

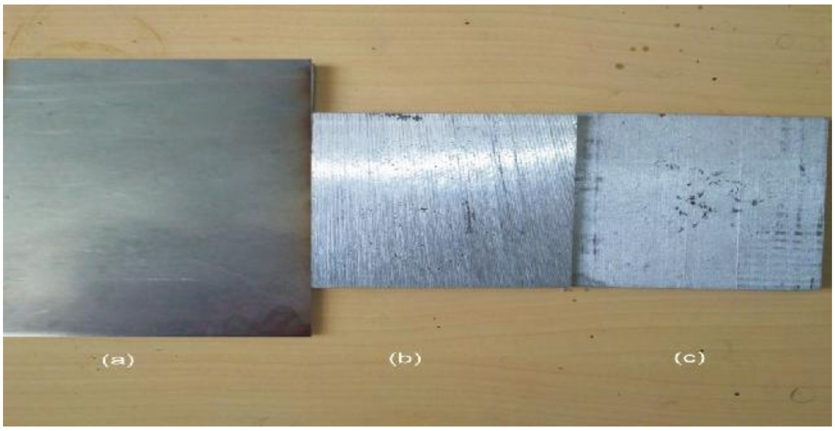


Figure 3.4 Workpiece before machining (a) AISI 304 (b) ALLOY (c) MMC

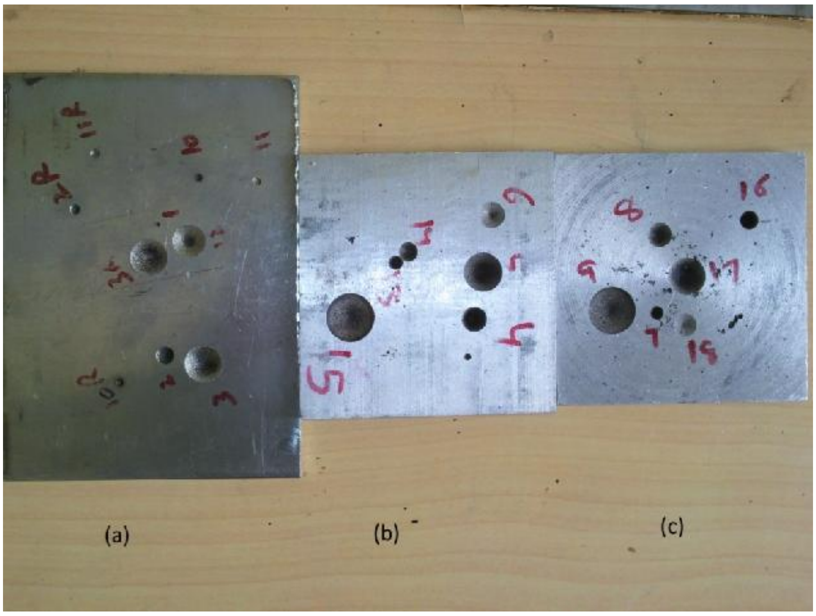


Figure 3.5 Workpiece after machining (a) AISI 304 (b) ALLOY (c) MMC

Figure 3.6 Electrode used at different angles namely 45°, 90° and 135°

Table 3.5: Chemical composition of workpiece material (%age)

Workpiece	Si	Mg	Cu	Ni	Fe	Mn	Zn	Pb	Al
Al-SiC MMC	16.85	0.9	0.25	0.82	0.25	0.05	Less than 0.2	Less than 0.2	Approximately 78
Al-Cu ALLOY	2	Less than 0.2	9.25	Less than 0.2	3	10.2	Less than 0.2	Less than 0.2	Approximately 75

Workpiece	C	Si	Mn	Cr	V	Ni	Mo	Cu	P	S
AISI 304	0.07	0.32	1.2	18.1	Less than 0.2	8.2	Less than 0.2	Less than 0.2	Less than 0.03	Less than 0.03

Table 3.6: Microhardness of workpiece material

Workpiece	AISI304	ALLOY	MMC
Microhardness(HVN)	90	105	130

CHAPTER 4

RESULTS AND ANALYSIS OF MRR

4.1 Introduction

The effects of parameters i.e. dielectric, workpiece, angle, concentration, current, pulse on time, pulse off time, powder were evaluated using ANOVA and factorial design analysis. A confidence interval of 95% has been used for the analysis. One repetition for each of 18 trials was completed to measure the Signal to Noise ratio (S/N Ratio).

4.2 Results for MRR

The result for MRR for each of the 18 treatment conditions is given in Table 4.1. The MRR is calculated from the loss of weight of the workpiece during performance trial:

$$\text{MRR} = \frac{W_i - W_f}{\rho t} \times 1000 \ \text{mm}^3/\text{min} \qquad \text{(Equation 4.1)}$$

Where Wi= Initial weight of workpiece (gm)

W_f = Final weight of workpiece (gm)

t= time period of trial (minutes)

ρ = density of the workpiece material (gm/cc)

Table 4.1: Results for MRR

Trial No.	**Dielectric**	**Workpiece**	**Angle (°)**	**Concen-tration (g/l)**	**Current (A)**	**Pulse On Time (μs)**	**Powder**	**MRR (mm^3/min)**	**S/N Ratio**	**Means**
1	Kerosene	AISI304	45	10	2	10	Si	0.726	2.770	0.726
2	Kerosene	AISI304	90	15	5	50	Cu	10.325	20.277	10.325
3	Kerosene	AISI304	135	20	8	100	Graphite	34.679	30.801	34.679
4	Kerosene	ALLOY	45	10	5	50	Graphite	7.401	17.386	7.401

5	Kerosene	ALLOY	90	15	8	100	Si	39.525	31.937	39.525
6	Kerosene	ALLOY	135	20	2	10	Cu	4.688	13.419	4.688
7	Kerosene	MMC	45	15	2	100	Cu	17.000	24.609	17.000
8	Kerosene	MMC	90	20	5	10	Graphite	19.550	25.823	19.550
9	Kerosene	MMC	135	10	8	50	Si	27.890	28.909	27.890
10	EDM oil	AISI304	45	20	8	50	Cu	28.899	29.217	28.899
11	EDM oil	AISI304	90	10	2	100	Graphite	15.840	23.995	15.840
12	EDM oil	AISI304	135	15	5	10	Si	17.815	25.015	17.815
13	EDM oil	ALLOY	45	15	8	10	Graphite	15.270	23.676	15.270
14	EDM oil	ALLOY	90	20	2	50	Si	17.635	24.927	17.635
15	EDM oil	ALLOY	135	10	5	100	Cu	27.070	28.649	27.070
16	EDM oil	MMC	45	20	5	100	Si	39.979	32.036	39.979
17	EDM oil	MMC	90	10	8	10	Cu	17.285	24.753	17.285
18	EDM oil	MMC	135	15	2	50	Graphite	13.334	22.499	13.334

4.3 ANOVA for Means of MRR

The results for MRR were analysed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean MRR at 95% confidence interval is given in Table 4.2. The variance data for each factor and their interactions were F-tested to find significance of each. ANOVA table shows the pulse on time (F value 42.56), current (F value 37.14), concentration (F value 10.38) and Powder type (F value 7.96) are the significant factors that affect the MRR. All remaining factors are insignificant to affect the MRR. It is observed that pulse on time is the most significant factor which contributes to MRR followed by current, concentration and type of powder used. Main effect plot for MRR are shown in Figure 4.1 that shows that MRR increases with increase in current from 2 A to 8A.The MRR increase with increase in concentration with MRR maximum at 20 g/l and minimum at 10g/l. MRR is maximum when pulse on time is 100µs and minimum at 10 µs. Silicon powder showed maximum MRR. Table 4.3 shows ranks to various factors: pulse on time has highest rank, most significant that affecting MRR. The angle is least significant in MRR.

Table 4.2: ANOVA for Means of MRR

Source	**SS**	**v**	**V**	**F**	**F (critical)**	**SS'**	**%age contribution**	**Status**
Dielectric	54.56	1	54.56	5.44	7.71			Insignificant
Workpiece	70.92	2	35.46	3.53				Insignificant
Angle	22.73	2	11.365	1.13				Insignificant
Concentration	208.21	2	104.105	10.38	6.94	166.35	7.71	Significant
Current	745.11	2	372.555	37.14	6.94	703.25	32.63	Significant
Pulse On Time	853.88	2	426.94	42.56	6.94	812.02	37.67	Significant
Powder	159.65	2	79.825	7.96	6.94	117.79	5.46	Significant
Error	40.13	4	10.0325					
TOTAL	2155.19	17	126.7759					
e-pooled	188.34	9	20.92667				16.50	

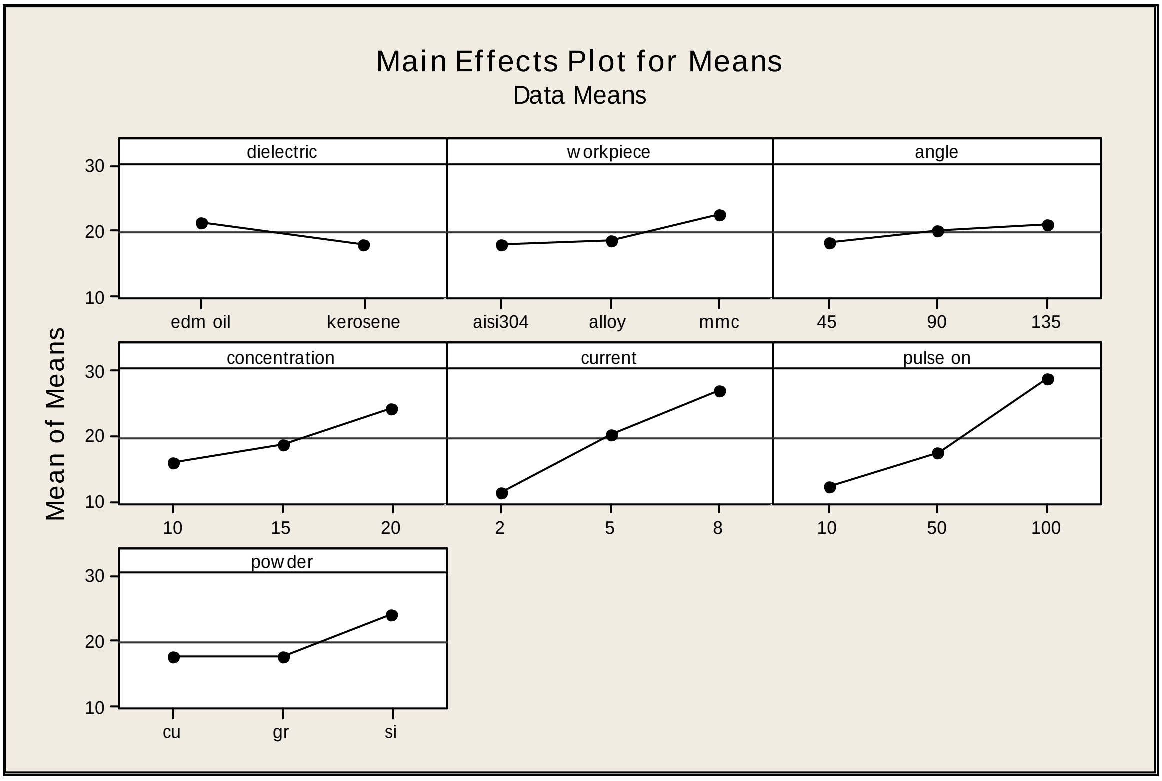


Figure 4.1: Main Effects Plot for Means for MRR

Table 4.3: Response table for means of MRR

Level	Dielectric	Workpiece	Angle	Concentration	Current	Pulse on	Powder
1	21.46	18.05	18.21	16.04	11.54	12.56	17.54
2	17.98	18.6	20.03	18.88	20.36	17.58	17.68
3		22.51	20.91	24.24	27.26	29.02	23.93
Delta	3.48	4.46	2.7	8.2	15.72	16.46	6.38
Rank	6	5	7	3	2	1	4

4.4 ANOVA for S/N Ratio of MRR

The S/N ratio consolidates several repetitions into one value and is an indication of the amount of variation present. The S/N ratio has been calculated to identify the major contributing factors and interactions that cause variation in the MRR. MRR is “Higher is better” type response which is given by:

HB: S/Nratio=$-10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^{-2}\right]$ (Equation 4.2)

Table 4.4 shows the ANOVA for S/N ratio for MRR at 95% confidence interval. The current is the most significant factor in affecting MRR followed by workpiece and angle according to F-test. Main effect plot for S/N ratios for MRR are shown in Figure 2.

Table 4.4: ANOVA for S/N ratio of MRR

Source	SS	v	V	F	F(critical)	SS'	%age contribution	Status
Dielectric	109.41	1	109.41	5.02	7.71			Insignificant
Workpiece	86.58	2	43.29	1.98				Insignificant
Angle	77.63	2	38.81	1.78				Insignificant
Concentration	113.77	2	56.88	2.61				Insignificant
Current	340.67	2	170.33	7.81	6.94	267.40	23.47	Significant
Pulse On Time	322.05	2	161.02	7.38	6.94	248.78	21.84	Significant
Powder	1.58	2	0.79	0.04				Insignificant

Error	87.24	4	21.81					
Total	1138.92	17	66.99					
e-pooled	476.2	13	36.63				54.67	

Table 4.5: Response table for S/N ratio of MRR

Level	Dielectric	Workpiece	Angle	Concentration	Current	Pulse on	Powder
1	26.09	21.09	20.69	20.15	17.78	18.32	23.49
2	21.15	23.33	25.29	24.67	24.86	23.87	24.03
3		26.44	24.88	26.04	28.22	28.67	23.34
Delta	4.93	5.35	4.59	5.88	10.44	10.35	0.69
Rank	5	4	6	3	1	2	7

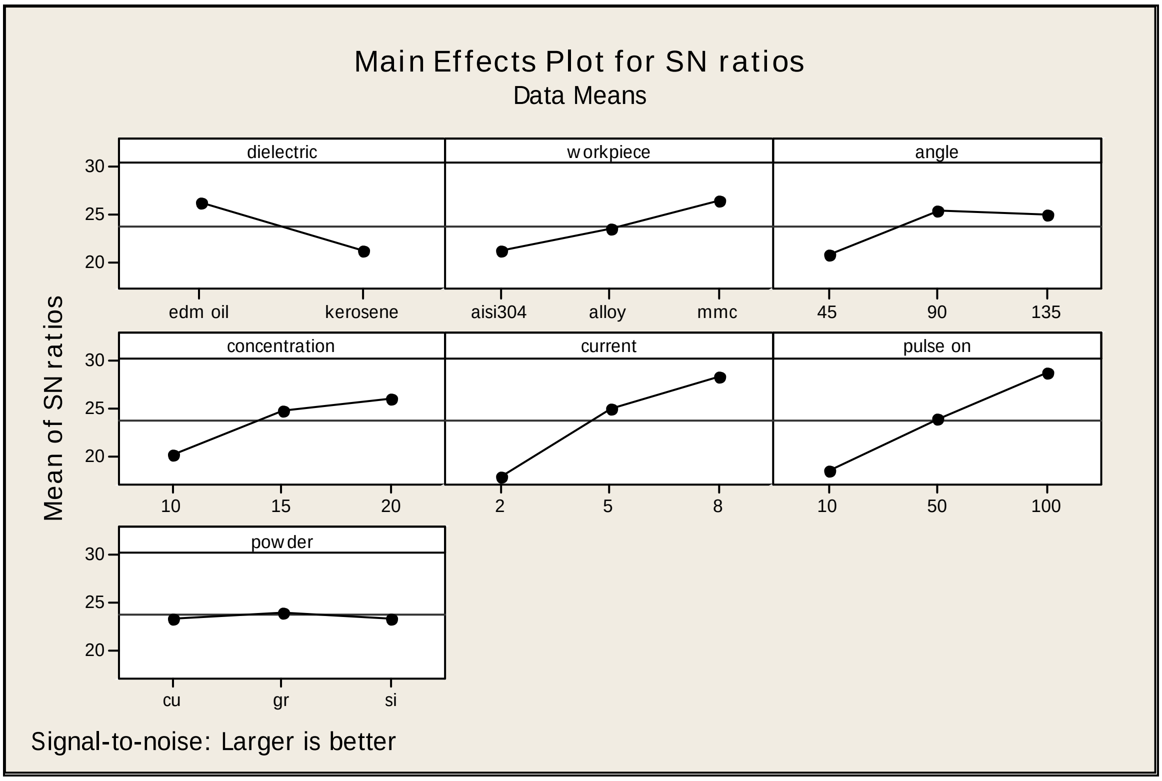


Figure 4.2: Main Effects Plot of MRR for S/N ratio

4.5. Optimal Design for MRR

In this experimental analysis, the main effect plot in Figure 4.1 was used to estimate the mean MRR. From the Table 4.6, it is observed that the highest MRR was to be observed when workpiece was machined with Silicon powder with concentration of 20 g/l at 8A current with pulse on time of 100µs. In S/N ratio, highest MRR was to be observed when workpiece was machined with pulse on time of 100µs at 8 A current. So, best values of MRR were suggested if workpiece is machined at 8 A current having Silicon powder with concentration of 20 g/l at pulse on time of 100µs.

Table 4.6 Significant factors and interactions

Factors	Affecting mean		Affecting variation(S/N ratio)	
	Contribution	Best Level	Contribution	Best Level
Dielectric(A)	Insignificant	-	Insignificant	-
Workpiece(B)	Insignificant	-	Insignificant	-
Angle(C)	Insignificant	-	Insignificant	-
Concentration(D)	Significant	Level-3(20g/l)	Insignificant	-

Current(E)	Significant	Level-3(8A)	Significant	Level-3(8A)
Pulse On Time(F)	Significant	Level-3 (100μs)	Significant	Level-3 (100μs)
Powder(G)	Significant	Level-3(Silicon)	Insignificant	-

Estimating the mean for MRR

In experimental analysis, MRR is a higher average response is better (HB) characteristic. Depending on the characteristic, different treatment combinations has been chosen to obtain satisfactory analysis. After conducting the experiments the optimum treatment condition within the experiments determined on the basis of prescribed combination of factor levels was determined to one of those in the experiment.

The mean value of MRR ($\bar{T}$) is 19.71. The formula for calculating the theoretical optimal value is as under:

$(MRR)_{opt} = \bar{T} + (D_3 - \bar{T}) + (E_3 - \bar{T}) + (F_3 - \bar{T}) + (G_3 - \bar{T})$

= 19.71+ (24.23-19.71) + (27.25-19.71) + (29.01-19.71) + (23.92 -19.71)

= 45.2887mm^3/min

Confidence Interval around the Estimated Mean

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

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

α= risk (0.05) confidence= 1-α

v_1= dof for mean which is always = 1

v_2= dof for error = v_e

ηeff = No. Of tests under that condition using the particular factors

ηeff =N/ (1+ dof $_{D+E+F+G}$) = 18/ (1+2+2+2+2) =2

$CI = \sqrt{(7.71 * 20.92/2)}$

$= 8.98$

So, the Confidence Interval around the MRR is given by 45.2887 $\pm$8.98 mm^3/min.

CHAPTER 5

RESULTS AND ANALYSIS OF TWR

5.1 Introduction

The effects of parameters i.e. dielectric, workpiece, angle, concentration, current, pulse on time, pulse off time, powder were evaluated using ANOVA and factorial design analysis. A confidence interval of 95% has been used for the analysis. One repetition for each of 18 trials was completed to measure the Signal to Noise ratio (S/N Ratio).

5.2 Results for TWR

The result for TWR for each of the 18 treatment conditions is given in Table 5. 1. The TWR is calculated from the loss of weight of the tool during performance trial:

$$TWR = \frac{T_i - T_f}{\rho t} \times 1000 \text{ mm}^3/\text{min} \qquad \text{(Equation 5.1)}$$

Where T_i = Initial weight of tool (gm)

T_f = Final weight of tool (gm)

t= time period of trial (minutes)

ρ = density of the tool material (gm/cc)

Table 5.1: RESULTS FOR TWR

Trial No.	**Dielectric**	**Workpiece**	**Angle (°)**	**Concentration (g/l)**	**Current (A)**	**Pulse On Time (μs)**	**Powder**	**TWR (m m^3 /min)**	**S/N**	**Means**
1	Kerosene	AISI304	45	10	2	10	Si	0.067	23.38	0.067
2	Kerosene	AISI304	90	15	5	50	Cu	1.023	-0.201	1.023
3	Kerosene	AISI304	135	20	8	100	Graphite	3.714	-11.39	3.714
4	Kerosene	Alloy	45	10	5	50	Graphite	0.505	5.934	0.505

5	Kerosene	Alloy	90	15	8	100	Si	3.350	-10.50	3.350
6	Kerosene	Alloy	135	20	2	10	Cu	0.166	15.56	0.166
7	Kerosene	MMC	45	15	2	100	Cu	0.710	2.973	0.710
8	Kerosene	MMC	90	20	5	10	Graphite	1.975	-5.911	1.975
9	Kerosene	MMC	135	10	8	50	Si	0.795	1.987	0.795
10	EDM Oil	AISI304	45	20	8	50	Cu	3.337	-10.46	3.337
11	EDM Oil	AISI304	90	10	2	100	Graphite	1.121	-0.998	1.121
12	EDM Oil	AISI304	135	15	5	10	Si	0.987	0.108	0.987
13	EDM Oil	Alloy	45	15	8	10	Graphite	0.946	0.477	0.946
14	EDM Oil	Alloy	90	20	2	50	Si	1.215	-1.696	1.215
15	EDM Oil	Alloy	135	10	5	100	Cu	1.485	-3.434	1.485
16	EDM Oil	MMC	45	20	5	100	Si	3.765	-11.51	3.765
17	EDM Oil	MMC	90	10	8	10	Cu	0.494	6.123	0.494
18	EDM Oil	MMC	135	15	2	50	Graphite	0.207	13.63	0.207

5.3 ANOVA for Means of TWR

The results for TWR were analysed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean TWR at 95% confidence interval is given in Table 5.2. The variance data for each factor and their interactions were F-tested to find significance of each. ANOVA table shows the current (F value 14.86), concentration (F value 17), pulse on time (F value 16.57) factors that affects the TWR. All remaining factors are insignificant to affect the TWR. It is observed that concentration is the most significant factor which contributes to TWR followed by pulse on time and current. Main effect plot for TWR are shown in Figure 5.1 that shows that TWR increases with increase in current from 2 to 8 A.TWR increases with increase in value of concentration with 10 g/l showing minimum TWR and 20 g/l showing maximum TWR. Pulse on time has direct relation with TWR, when pulse on time increases, TWR increases. Table 5.3 shows ranks to various factors: concentration has highest rank, most significant that affecting TWR. The dielectric, powder is least significant in TWR.

Table 5.2: ANOVA for Means of TWR

Sources	**SS**	**V**	**V**	**F**	**F(critical)**	**SS'**	**%age contribution**	**Status**
Dielectric	0.087	1	0.08	0.36	7.71			Insignificant
Workpiece	0.67	2	0.33	1.37				Insignificant
Angle	0.40	2	0.20	0.82				Insignificant
Concentration	8.33	2	4.16	17	6.94	7.81	29.34	Significant
Current	7.28	2	3.64	14.86	6.94	6.76	25.39	Significant
Pulse On Time	8.12	2	4.06	16.57	6.94	7.60	28.55	Significant
Powder	0.73	2	0.36	1.51				Insignificant
Error	0.98	4	0.24					
TOTAL	26.63	17	1.56					
e-pooled	2.8798	11	0.2618				16.71	

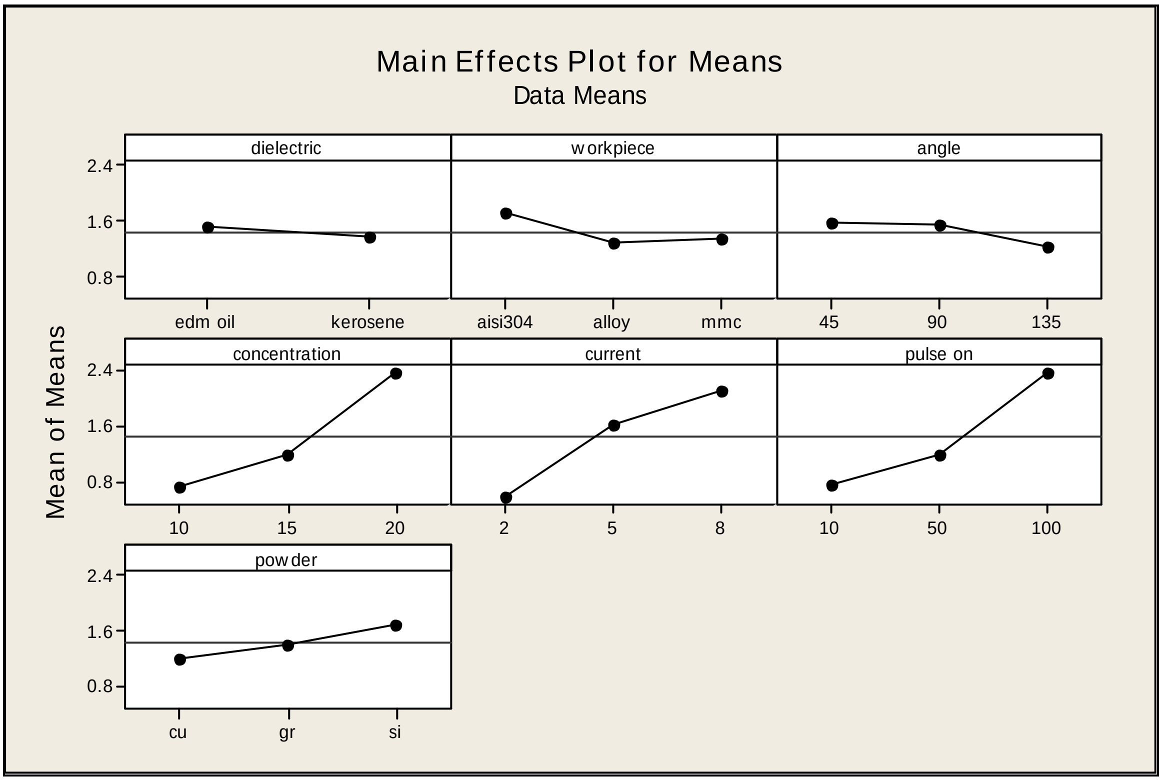


Figure 5.1: Main Effects Plot for Means for TWR

Table 5.3: Response table for Mean of TWR

Level	Dielectric	Workpiece	Angle	Concentration	Current	Pulse On Time	Powder
1	1.5069	1.7088	1.5554	0.7449	0.5816	0.7729	1.2028
2	1.3676	1.2782	1.5301	1.2044	1.6236	1.1809	1.4118
3		1.3247	1.2261	2.3625	2.1064	2.3579	1.6971
Delta	0.1393	0.4306	0.3293	1.6176	1.5248	1.585	0.4942
Rank	7	5	6	1	3	2	4

5.4 ANOVA for S/N Ratio of TWR

The S/N ratio consolidates several repetitions into one value and is an indication of the amount of variations present. The S/N ratio has been calculated to identify the major contributing factors and interactions that cause variation in the TWR. TWR is “Lower is better” type response which is given by:

LB: S/N ratio= $-10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right]$ (Equation 5.2)

Table 5.4 shows the ANOVA for S/N ratio for TWR at 95% confidence interval. The current is the most significant factor in affecting TWR followed by pulse on time according to F-test. Main effect plot for S/N ratios for TWR are shown in Figure 5.2.

Table 5.4: ANOVA for S/N ratio of TWR

Sources	**SS**	**v**	**V**	**F**	**F(critical)**	**SS'**	**%age contribution**	**Status**
Dielectric	48.7	1	48.7	2	7.71			Insignificant
Workpiece	4.62	2	2.31	0.09				Insignificant
Angle	82.61	2	41.30	1.7				Insignificant
Concentration	285.24	2	142.62	5.85				Insignificant
Current	586.82	2	293.41	12.04	6.94	505.70	31.94	Significant
Pulse On Time	469.24	2	234.62	9.63	6.94	388.12	24.51	Significant
Powder	8.61	2	4.305	0.18				Insignificant
Error	97.46	4	24.36					
TOTAL	1583.3	17	93.13					
e-pooled	527.24	13	40.55				43.54	

Table 5.5: Response table for S/N ratio of TWR

Level	**Dielectric**	**Workpiece**	**Angle**	**Concentration**	**Current**	**Pulse On Time**	**Powder**
1	-0.86289	0.0716	1.79797	5.50008	8.81261	6.62607	1.76024

2	2.42671	1.05801	-2.1978	1.08258	-2.50356	1.53236	0.29056
3		1.21611	2.74563	-4.23694	-3.96332	-5.81271	0.29492
Delta	3.2896	1.14451	4.94351	9.73703	12.77593	12.43879	1.46968
Rank	5	7	4	3	1	2	6

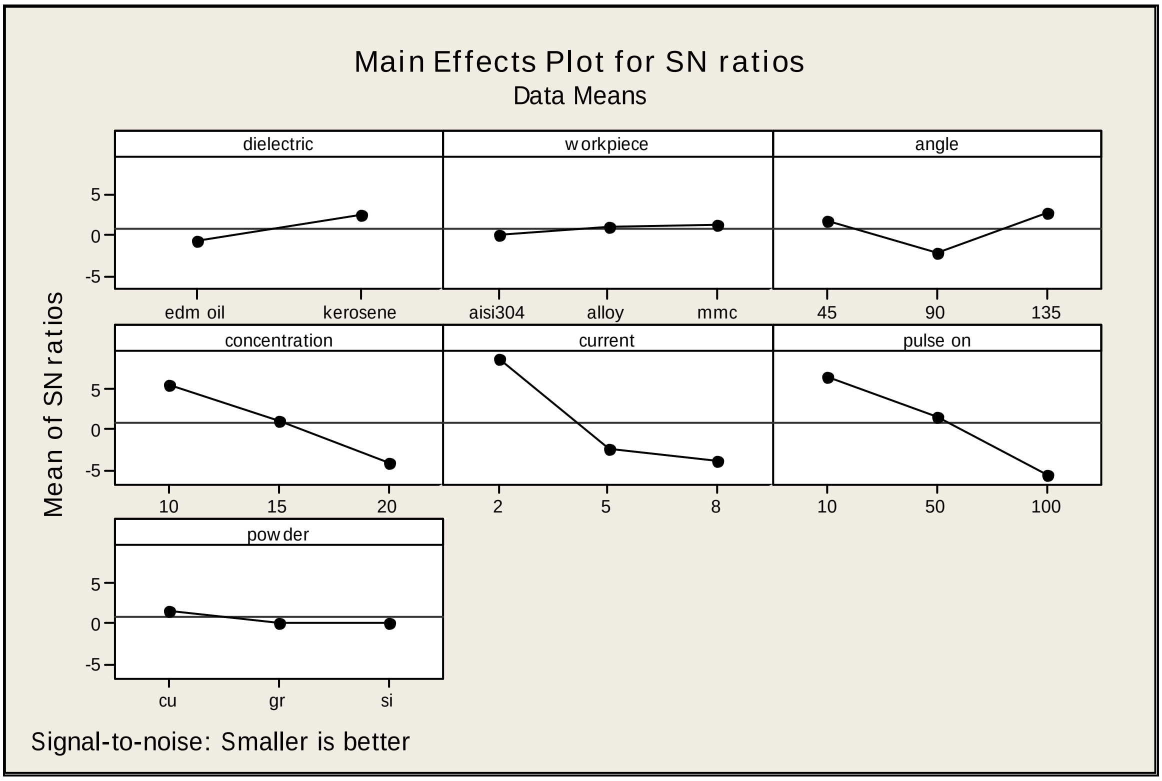


Figure 5.2: Main Effects Plot of TWR for S/N ratio

5.5 Optimal Design for TWR

In this experimental analysis, the main effect plot in Figure 5.1 was used to estimate the mean TWR. From the Table 5.6, it is observed that the lowest TWR was to be observed when workpiece was machined with powder concentration of 10 (g/l) at 2 A current with pulse on time of 10 µs. In S/N ratio, highest TWR was to be observed when workpiece was machined at 2 A current with pulse on time of

10 µs. So, best values of TWR was suggested if workpiece machined with powder concentration of 10 (g/l) at 2 A current with pulse on time of 10 µs.

Table 5.6 Significant factors and interactions

Factors	Affecting mean		Affecting variation(S/N ratio)	
	Contribution	Best Level	Contribution	Best Level
Dielectric(A)	Insignificant	-	Insignificant	-
Workpiece(B)	Insignificant	-	Insignificant	-
Angle(C)	Insignificant	-	Insignificant	-
Concentration(D)	Significant	Level-1(10g/l)	Insignificant	-
Current(E)	Significant	Level-1(2A)	Significant	Level-1(2A)
Pulse On Time(F)	Significant	Level-1(10µS)	Significant	Level-1(10µS
Powder(G)	Insignificant	-	Insignificant	-

Estimating the mean for TWR

In experimental analysis, TWR is a lower average response is better (LB) characteristic. Depending on the characteristic, different treatment combinations has been chosen to obtain satisfactory analysis. After conducting the experiments the optimum treatment condition within the experiments determined on the basis of prescribed combination of factor levels was determined to one of those in the experiment.

The mean value of TWR ($\bar{T}$) is 0.65. The formula for calculating the theoretical optimal value is as under:

$$(TWR)_{opt} = \bar{T} + (D_1 - \bar{T}) + (E_1 - \bar{T}) + (F_1 - \bar{T})$$

$$= 0.65 + (0.7448-0.65) + (0.7816-0.65) + (0.7729-0.65)$$

$= 1.02\ mm^3/min$

Confidence Interval around the Estimated Mean

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

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

α= risk (0.05)   confidence= 1-α

v_1= dof for mean which is always = 1

v_2= dof for error = v_e

η_{eff} = No. of tests under that condition using the particular factors

$\eta_{eff} = N/(1+ \text{dof}_{D+E+F}) = 18/(1+2+2+2) = 2.5714$

CI=√(7.71*0.2618/2.5714)

=0.68

So, the Confidence Interval around the TWR is given by 1.02 $\pm$ 0.68 mm^3/min.

CHAPTER 6

RESULTS AND ANALYSIS OF WR

6.1 Introduction

The effects of parameters i.e. dielectric, workpiece, angle, concentration, current, pulse on time, pulse off time, powder were evaluated using ANOVA and factorial design analysis. A confidence interval of 95% has been used for the analysis. One repetition for each of 18 trials was completed to measure the Signal to Noise ratio (S/N Ratio).

6.2 Results for WR

The result for WR for each of the 18 treatment conditions is given in Table 6.1. The WR is calculated from the ratio of TWR and MRR during performance trial:

$$WR = \frac{TWR}{MRR} \qquad \text{(Equation 6.1)}$$

Where

WR= Wear Ratio (dimensionless quantity)
TWR= Tool Wear Rate (mm^3/min)
MRR= Material Removal Rate (mm^3/min)

Table 6. 1: Results for WR

Trial No.	Dielectric	Workpiece	Angle (°)	Concentration (g/l)	Current (A)	Pulse On Time (µS)	Powder	WR	S/N	Means
1	Kerosene	AISI304	45	10	2	10	Si	0.093	20.617	0.093
2	Kerosene	AISI304	90	15	5	50	Cu	0.099	20.076	0.099
3	Kerosene	AISI304	135	20	8	100	Graphite	0.107	19.404	0.107

4	Kerosene	Alloy	45	10	5	50	Graphite	0.068	23.320	0.068
5	Kerosene	Alloy	90	15	8	100	Si	0.084	21.435	0.084
6	Kerosene	Alloy	135	20	2	10	Cu	0.035	28.989	0.035
7	Kerosene	MMC	45	15	2	100	Cu	0.041	27.583	0.041
8	Kerosene	MMC	90	20	5	10	Graphite	0.101	19.911	0.101
9	Kerosene	MMC	135	10	8	50	Si	0.028	30.896	0.028
10	EDM Oil	AISI304	45	20	8	50	Cu	0.115	18.748	0.115
11	EDM Oil	AISI304	90	10	2	100	Graphite	0.070	22.996	0.070
12	EDM Oil	AISI304	135	15	5	10	Si	0.055	25.124	0.055
13	EDM Oil	Alloy	45	15	8	10	Graphite	0.061	24.154	0.061
14	EDM Oil	Alloy	90	20	2	50	Si	0.068	23.231	0.068
15	EDM Oil	Alloy	135	10	5	100	Cu	0.054	25.215	0.054
16	EDM Oil	MMC	45	20	5	100	Si	0.094	20.520	0.094
17	EDM Oil	MMC	90	10	8	10	Cu	0.028	30.877	0.028
18	EDM Oil	MMC	135	15	2	50	Graphite	0.015	36.138	0.015

6.3 ANOVA for Means for WR

The results for WR were analysed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean WR at 95% confidence interval is given in Table 6.2. The variance data for each factor and their interactions were F-tested to find significance of each. ANOVA table shows that only Workpiece (F value 8.77) is significant factor. Remaining factors are insignificant to WR.

Table 6.2: ANOVA for Means of WR

Sources	SS	v	V	F	F(critical)	SS'	%age contribution	Status
Dielectric	0.000484	1	0.000484	1.78	7.71			Insignificant
Workpiece	0.004754	2	0.002377	8.77	6.94	0.003332	21.60	Significant
Angle	0.003137	2	0.001569	5.79				Insignificant
Concentration	0.003261	2	0.001631	6.02				Insignificant
Current	0.001884	2	0.000942	3.48				Insignificant
Pulse On Time	0.000544	2	0.000272	1				Insignificant
Powder	0.000272	2	0.000136	0.5				Insignificant
Error	0.001084	4	0.000271					
TOTAL	0.01542	17	0.000907					
e-pooled	0.010666	15	0.000711				78.39	

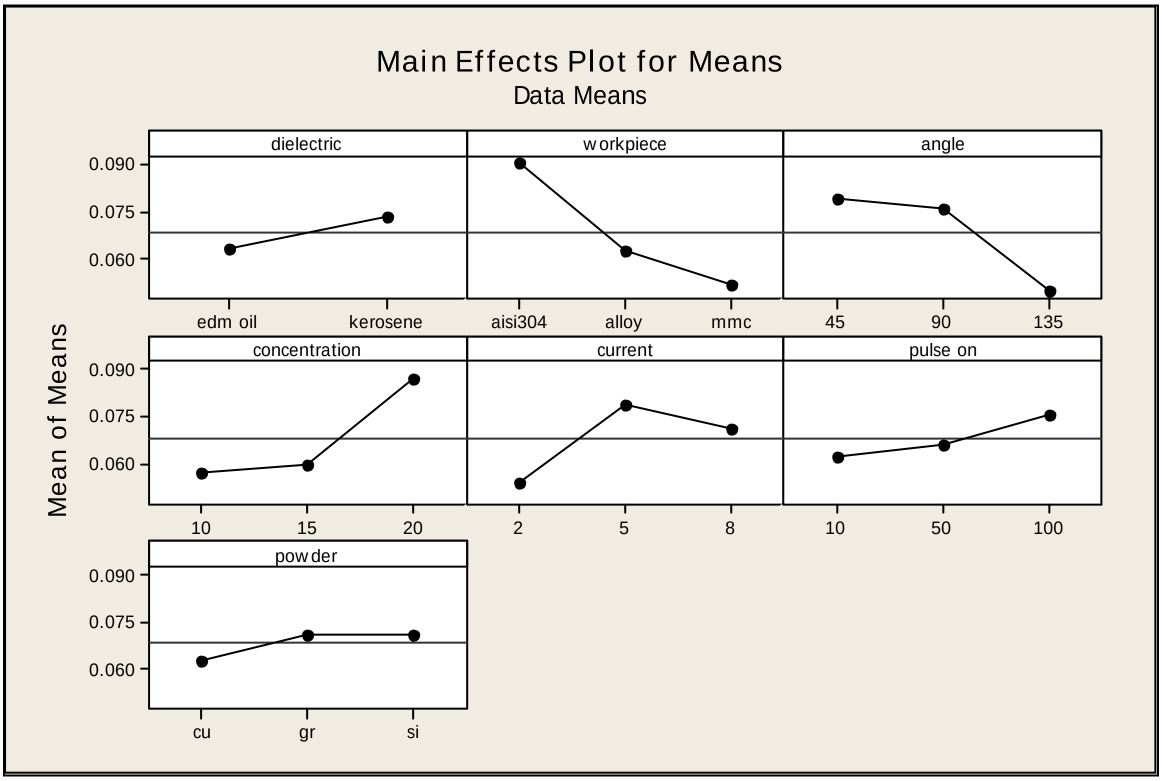


Figure 6.1: Main Effects Plot for Means for WR

Table 6.3: Response table for Mean of WR

Level	Dielectric	workpiece	angle	Concentration	current	pulse on	Powder
1	0.06288	0.09019	0.07913	0.05736	0.0543	0.06261	0.06256
2	0.07324	0.06238	0.07554	0.05978	0.07881	0.06599	0.07079
3		0.05161	0.04951	0.08705	0.07108	0.07559	0.07083
Delta	0.01037	0.03857	0.02963	0.02969	0.02451	0.01297	0.00827
Rank	6	1	3	2	4	5	7

6.4 ANOVA for S/N Ratio for WR

The S/N ratio consolidates several repetitions into one value and is an indication of the amount of variation present. The S/N ratio has been calculated to identify the major contributing factors and interactions that cause variation in the WR. WR is "Lower is better" type response which is given by:

LB: S/N ratio= $-10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right]$ (Equation 6.2)

Table 6.4 shows the ANOVA for S/N ratio for WR at 95% confidence interval. The workpiece, angle, concentration and current are the significant factor in affecting WR according to F-test. Main effect for S/N ratios for WR is shown in Figure 6.2.

Table 6.4: ANOVA for S/N ratio of WR

Sources	SS	v	V	F	F (critical)	SS'	%age contribution	Status
Dielectric	12.12	1	12.12	3.3	7.71			Insignificant
Workpiece	126.49	2	63.24	17.21	6.94	113.88	28.99	Significant
Angle	94.72	2	47.36	12.89	6.94	82.12	20.90	Significant
Concentration	60.93	2	30.46	8.29	6.94	48.33	12.30	Significant
Current	53.91	2	26.95	7.34	6.94	41.30	10.51	Significant
Pulse On Time	22.05	2	11.02	3				Insignificant
Powder	7.84	2	3.92	1.07				Insignificant
Error	14.7	4	3.67					
TOTAL	392.79	17	23.10					
e-pooled	56.72	9	6.30				27.27	

Table 6.5: Response table for S/N ratio of WR

Level	dielectric	workpiece	angle	concentration	current	pulse on	Powder
1	25.22	21.16	22.49	25.65	26.59	24.95	25.25
2	23.58	24.39	23.09	25.75	22.36	25.4	24.32
3		27.65	27.63	21.8	24.25	22.86	23.64
Delta	1.64	6.49	5.14	3.95	4.23	2.54	1.61
Rank	6	1	2	4	3	5	7

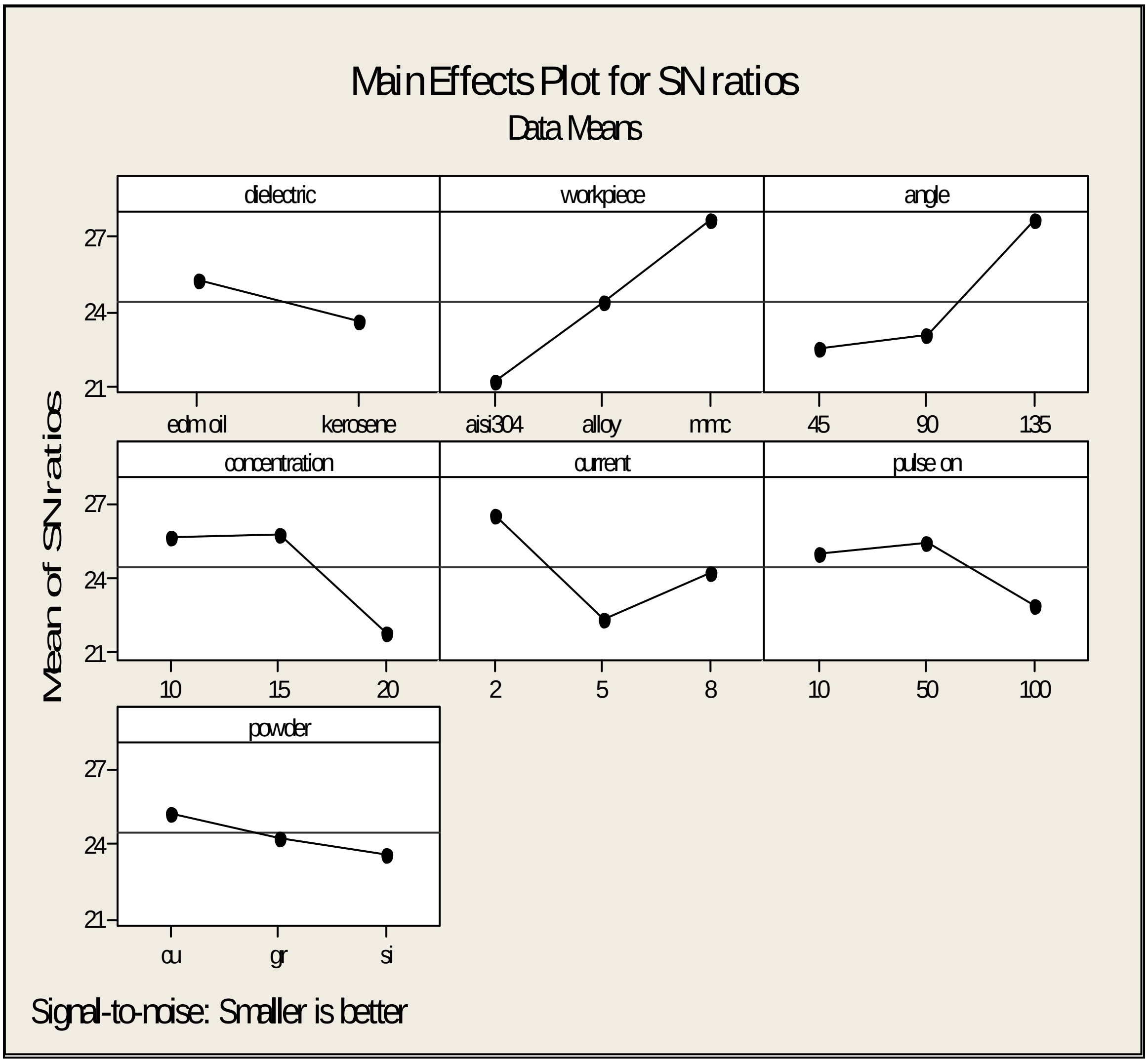


Figure 6.2: Main Effects Plot of WR for S/N ratio

6.5 Optimal Design for WR

In this experimental analysis, the main effect plot in Figure 6.1 was used to estimate the mean WR. From the Table 6.6, In case of Means, best WR was found if MMC is machined. In S/N ratio, lowest WR was to be observed when workpiece (MMC) was machined at 2 A current at angle of 135° with powder concentration of 15 g/l. So, a best value of WR was suggested if workpiece (MMC) is machined at 2 A current at angle of 135° with powder concentration of 15 g/l.

Table 6.6 Significant factors and interactions

Factors	Affecting mean		Affecting variation(S/N ratio)	
	Contribution	Best Level	Contribution	Best Level
Dielectric(A)	Insignificant	-	Insignificant	-
Workpiece(B)	Significant	Level-3(MMC)	Significant	Level-3(MMC)
Angle(C)	Insignificant	-	Significant	Level-3(135°)
Concentration(D)	Insignificant	-	Significant	Level-2(15 g/l)
Current(E)	Insignificant	-	Significant	Level-1(2A)
Pulse On Time(F)	Insignificant	-	Insignificant	-
Powder(G)	Insignificant	-	Insignificant	-

Estimating the mean for WR

In experimental analysis, WR is a lower average response is better (LB) characteristic. Depending on the characteristic, different treatment combinations has been chosen to obtain satisfactory analysis. After conducting the experiments the optimum treatment condition within the experiments determined on the basis of prescribed combination of factor levels was determined to one of those in the experiment.

The mean value of WR ($\bar{T}$) is 0.26. The formula for calculating the theoretical optimal value is as under:

$(WR)_{opt} = \bar{T} + ((B_3 - \bar{T}) + ((C_3 - \bar{T}) + ((D_2 - \bar{T}) + ((E_1 - \bar{T})$

= 0.26+ (0.3-0.26) + (0.24-0.26) + (0.23-0.26) + (0.36-0.26)

= 0.35

Confidence Interval around the Estimated Mean

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

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

α= risk (0.05)   confidence= 1-α

v_1= dof for mean which is always = 1

v_2= dof for error = v_e

ηeff = No. Of tests under that condition using the particular factors

ηeff =N/ (1+ dof $_{B+C+D+E}$) = 18/(1+2+2+2+2)=2

CI=√(7.71*0.0007/2)

= 0.05

So, the Confidence Interval around the WR is given by 0.35± 0.05.

CHAPTER 7

RESULTS AND ANALYSIS OF GEOMETRIC ACCURACY

7.1 Introduction

In this experiment, the profile or geometric accuracy has been studied using a tool with different front angle such as 45°, 90° and 135° under various parameters such as current, dielectric, powder concentration, pulse on time, powder on different materials. The angle generated on the workpiece is measured to evaluate the accuracy of the profile produced.

7.2 Materials used

The profile or geometric accuracy has been studied using a copper tool with different front angle such as 45°, 90° and 135°. The dielectric used for experimentation was taken as Kerosene and EDM oil. Silicon, Graphite and Copper powders were used to see the effect on AISI 304, Alloy and Composite.

7.3 Equipment's used

Vernier calliper was used to measure the angle generated on the workpiece.

7.4 Parameters used

Copper tool is used with different front angle such as 45°, 90° and 135°. The various parameters for each of the trial are shown in Table 7.1.

Table 7.1: The various parameters in experimentation trial

Trail No.	Dielectric	Workpiece	Concentration (g/l)	Current (A)	Pulse On Time (μS)	Powder	Tool Front Angle (°)
1	Kerosene	AISI304	10	2	10	Si	45
2	Kerosene	AISI304	15	5	50	Cu	90
3	Kerosene	AISI304	20	8	100	Graphite	135
4	Kerosene	Alloy	10	5	50	Graphite	45

5	Kerosene	Alloy	15	8	100	Si	90
6	Kerosene	Alloy	20	2	10	Cu	135
7	Kerosene	MMC	15	2	100	Cu	45
8	Kerosene	MMC	20	5	10	Graphite	90
9	Kerosene	MMC	10	8	50	Si	135
10	EDM Oil	AISI304	20	8	50	Cu	45
11	EDM Oil	AISI304	10	2	100	Graphite	90
12	EDM Oil	AISI304	15	5	10	Si	135
13	EDM Oil	Alloy	15	8	10	Graphite	45
14	EDM Oil	Alloy	20	2	50	Si	90
15	EDM Oil	Alloy	10	5	100	Cu	135
16	EDM Oil	MMC	20	5	100	Si	45
17	EDM Oil	MMC	10	8	10	Cu	90
18	EDM Oil	MMC	15	2	50	Graphite	135

7.5 Results of Profile accuracy or Geometric accuracy

The experimentation trials as shown in Table 7.1 were carried out and the corresponding angle generated on the workpiece was calculated by using Vernier caliper. Vernier caliper was used to measure the diameter (d) and depth of cut (h) respectively. The diameter (d) and depth of cut (h) were used to calculate the angle generated on the workpiece (Ø) by using the formula given below:-

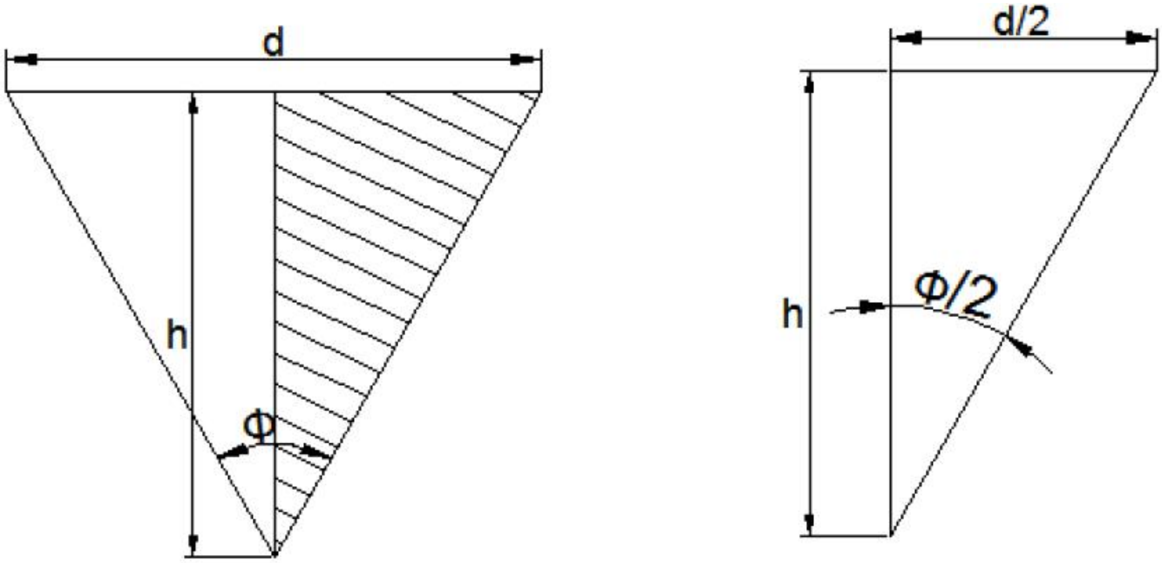


Figure 7.1: Diagram showing the calculation of the angle generated on the workpiece (Ø)

$$\text{Tan}\left(\frac{Ø}{2}\right) = \frac{d}{2h}$$

Where d= diameter of the cut on the workpiece,

h= depth of cut in the workpiece

The angle generated on the workpiece (Ø) in each of the experimentation trails are shown in Table 7.2.

Table 7.2: Angle generated on the workpiece (Ø) in each of the experimentation trials

Trial No.	Dielectric	Workpiece	Concent-ration (g/l)	Current (A)	Pulse On Time (µs)	Powder	Tool Front Angle (°)	Angle(Ø) Generated On The Workpiece (°)
1	Kerosene	AISI304	10	2	10	Si	45	50.05
2	Kerosene	AISI304	15	5	50	Cu	90	94.86
3	Kerosene	AISI304	20	8	100	Graphite	135	141.2
4	Kerosene	Alloy	10	5	50	Graphite	45	48.53
5	Kerosene	Alloy	15	8	100	Si	90	97.89

6	Kerosene	Alloy	20	2	10	Cu	135	137.36
7	Kerosene	MMC	15	2	100	Cu	45	47.34
8	Kerosene	MMC	20	5	10	Graphite	90	95.1
9	Kerosene	MMC	10	8	50	Si	135	142.39
10	EDM Oil	AISI304	20	8	50	Cu	45	51.1
11	EDM Oil	AISI304	10	2	100	Graphite	90	92.91
12	EDM Oil	AISI304	15	5	10	Si	135	138.53
13	EDM Oil	Alloy	15	8	10	Graphite	45	50.43
14	EDM Oil	Alloy	20	2	50	Si	90	94.11
15	EDM Oil	Alloy	10	5	100	Cu	135	139.4
16	EDM Oil	MMC	20	5	100	Si	45	49.61
17	EDM Oil	MMC	10	8	10	Cu	90	96.70
18	EDM Oil	MMC	15	2	50	Graphite	135	136.00

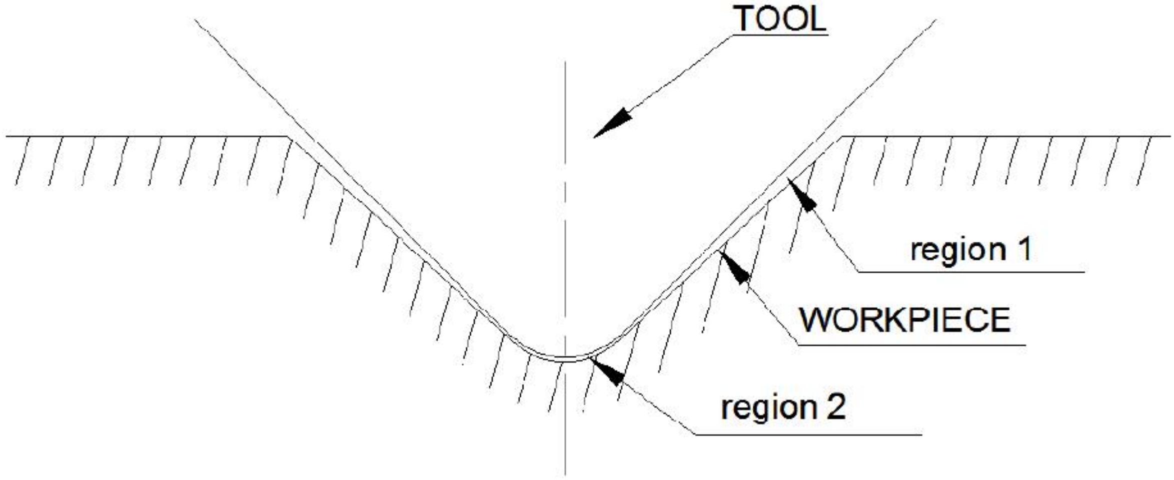


Figure 7.2: Diagram showing variation in the distance between the tool and workpiece

Figure 7.2 shows the variation in the distance between the tool and workpiece and Table 7.2 shows the angle generated on the workpiece (Ø).Due to smaller dimensions, it was not possible to find out the angle generated in Trial No. 1.It is quite clear that the angle generated on the workpiece (Ø) is high when tool front angle is small and vice-versa. The reason for this might be that when tool front angle is large then the distance between the tool and workpiece would remain less uneven and thus the spark energy remains more uniform at different places between tool and workpiece whereas when the tool front angle is small then the distance between the tool and workpiece would remain more uneven because when the tool moves from up to down into the workpiece, the sparking between the tool and workpiece starts at region 1 in the Figure 7.2 and thus the sparking at region 1 occurs for more time as compared to the region 2 and thus more machining takes place at region 1.It can also be concluded that AISI 304 shows minimum variation in tool front angle. With the increase of current and powder concentration, tool front angle increases. Hence it can be concluded that when the tool front angle is small then more variation occurs in sparking at different places between the tool and the workpiece and thus the angle generated on the workpiece is less accurate. Similarly, when tool front angle is large, the angle generated between the tool and workpiece is more accurate.

CHAPTER 8

RESULTS AND ANALYSIS OF SURFACE ROUGHNESS

8.1 Introduction

Surface Roughness (R_a) is the arithmetic average roughness of the deviations of the roughness profile from the central line along the measurement. It is a 'Lower is Better' phenomena. Surface Roughness was measured using the Perthometer; model M4Pi of Mahr, Germany available at SVIET, Banur. The equipment uses the stylus method of measurement, has profile resolution of 12 nm and measures roughness up to 100µm.

Surface Roughness $(R_a) = \frac{1}{L}\int_0^L |h(x)\, dx|$ (Equation 8.1)

where h(x) is the value of roughness profile & L is evaluation length

8.2 Results for R_a

The result for R_a for 15 treatment conditions is given in Table 8.1. Due to uneven shape of specimens, the testing was performed on different evaluating length which is also shown in Table 8.1.

Table 8.1: Results for R_a

Trial No.	Dielectric	Workpiece	Concent-ration (g/l)	Current (A)	Pulse On Time (µs)	Powder	Evaluating Length (mm)	R_a (µm)
2	Kerosene	AISI304	15	5	50	Cu	0.08	0.42
3	Kerosene	AISI304	20	8	100	Graphite	0.25	2.33
4	Kerosene	Alloy	10	5	50	Graphite	0.08	0.50

5	Kerosene	Alloy	15	8	100	Si	0.25	2.45
6	Kerosene	Alloy	20	2	10	Cu	0.08	1.95
7	Kerosene	MMC	15	2	100	Cu	0.08	1.97
8	Kerosene	MMC	20	5	10	Graphite	0.08	0.40
9	Kerosene	MMC	10	8	50	Si	0.25	3.59
12	EDM Oil	AISI304	15	5	10	Si	0.08	0.54
13	EDM Oil	Alloy	15	8	10	Graphite	0.08	0.12
14	EDM Oil	Alloy	20	2	50	Si	0.08	0.85
15	EDM Oil	Alloy	10	5	100	Cu	0.25	4.55
16	EDM Oil	MMC	20	5	100	Si	0.08	0.14
17	EDM Oil	MMC	10	8	10	Cu	0.25	1.95
18	EDM Oil	MMC	15	2	50	Graphite	0.08	0.71

It was not possible due to find out the value of R_a in Trial No.1, 10 and 11.Since, we are unable to find all the values and evaluation length is also different, so ANOVA can’t be applied in this case. From the above results, it can be concluded that current and roughness have direct relationship. With the increase of current, the value of surface roughness increases. So, maximum roughness was found in case of 8 A and minimum for 2 A. So, for minimum value of roughness, 2 A current is a better choice. It can also be found that the evaluation length has created large effect in value of Surface Roughness. 0.25 mm has shown higher value of roughness while 0.08 mm has shown comparatively low roughness value. It is also clear from above table that high powder concentration gives low surface roughness. So, for best surface roughness, use powder concentration of 20 g/l. With the increase in pulse on time, the surface roughness increases. So, for best value of surface roughness, pulse on time of 10 µs is recommended.

CHAPTER 9

FURTHER ANALYSIS

9.1 Introduction

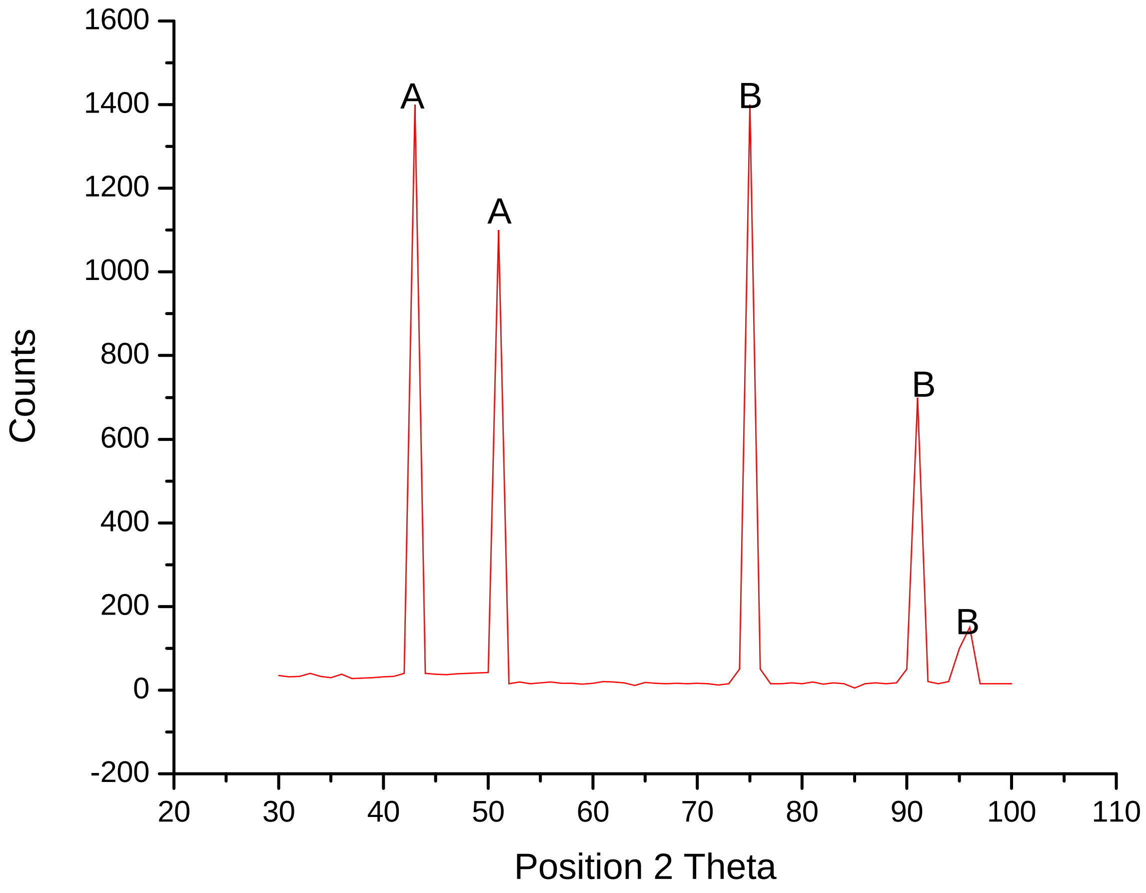
Further analysis of the machined surfaces after confirmation experiments was performed to find out surface composition and microstructure and it has been presented in this part. Surface composition was determined with the help of X-Ray diffraction (XRD) analysis and micro structural studies were carried out on a Scanning Electron Microscope (SEM).In this work, the effect of various input parameters i.e. current, dielectric, workpiece material, powder type, powder concentration, tool front angle and pulse on time on the surface properties of the workpiece material were evaluated. During machining, sparking between tool and workpiece takes place and causes very high rise in temperature and this temperature causes vaporization of the molten metal at the point of discharge. Due to very high temperature, the workpiece material is subjected to recrystallization of the metal grains and subsequent cooling of the heated metal causes change in the micro structure. The heating and cooling rate decides the shape, size of grains and properties of machined surface. Moreover transfer of material takes place from the powder suspended in the dielectric fluid and also from the electrode to the machined surface. The chemical composition of the machined surface was determined with the help of X-Ray Diffraction (XRD) analysis. Micro structural analysis was carried using Scanning Electron Microscope (SEM). During this analysis, chemical composition of machined surface and microstructure of machined surface was evaluated.

9.2 XRD Analysis

The material is transferred to the workpiece from the powder mixed in the dielectric fluid or from the electrode. It forms various compound on the surface of workpiece. To analyze this, the workpiece was tested for XRD on selected samples. The scan speed of 5°/minute was kept fixed for each test.

9.2.1 XRD of AISI 304

X-ray diffraction analysis at parameters namely current of 5A, pulse on time 50 µs, concentration 15g/l at angle of 90° with Kerosene in Cu powder on AISI 304 shows Fe_2O_3 (haematite) and a mixture of oxide of iron and chromium. This chromium oxide is the reason for formation of cracks which were verified by SEM analysis.

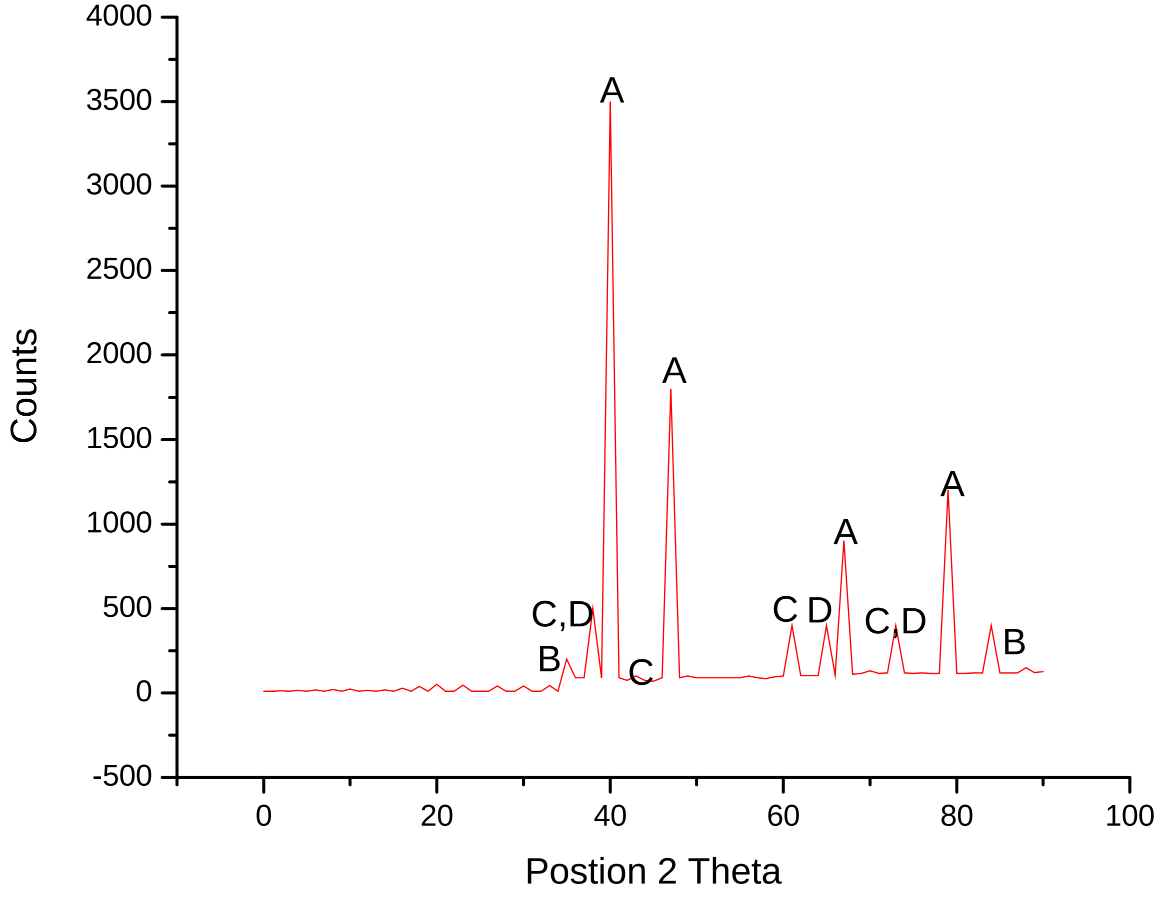


where **A** – Iron chromium oxide $(Fe_{0.6}\ Cr_{0.4})_2\ O_3$, **B**- Fe_2O_3 (hematite)

Figure 9.1: XRD analysis of AISI 304

9.2.2 XRD of MMC

XRD analysis at parameters namely 135° tool front angle with Kerosene in Si powder at current of 8A, pulse on time 50 µs, concentration 10g/l shows the presence of SiC, Aluminium, Aluminium oxide.

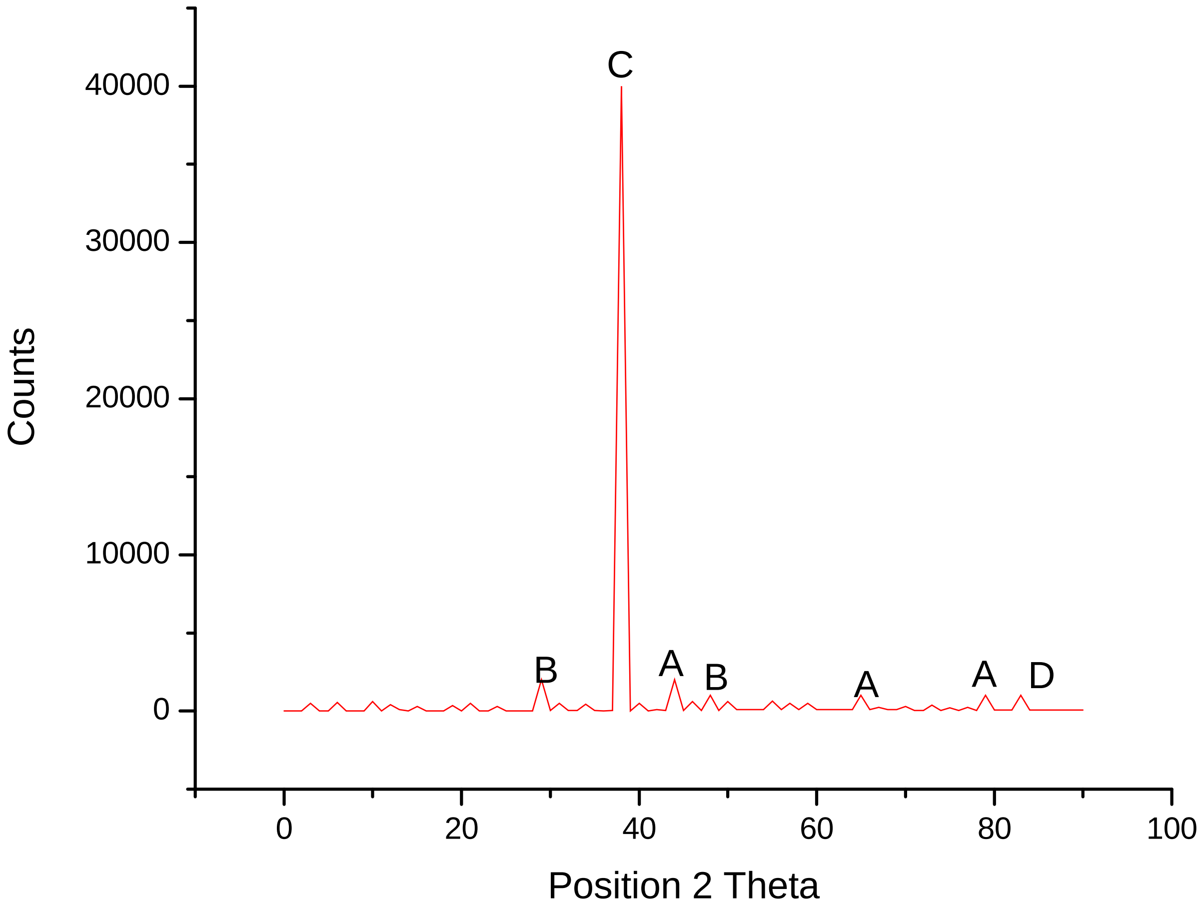


where **A**- Al_4C_3, **B**-Al, **C**- Al_2O_3, **D**-SiC

Figure 9.2: XRD analysis of MMC

9.2.3 XRD of ALLOY

XRD analysis at parameters namely 135° tool front angle with EDM Oil in Graphite powder with current of 5A, pulse on time 10 µs and concentration 15g/l shows the presence of Al, Si, Cu, Cu15Si4.



where **A**-Al, **B**-Si, **C**-Cu,**D**-$Cu_{15}Si_4$

Figure 9.3: XRD analysis of ALLOY

9.3 Microstructure Analysis

Microstructure analysis was carried out on six selected samples using Scanning Electron Microscope to study the change in microstructure after machining. The samples were prepared as per standard before SEM analysis on three different magnifications namely, 200 X, 500 X and 1000X.

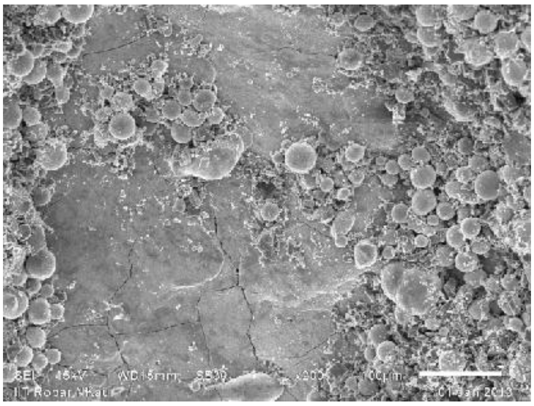
9.3.1 Preparing Samples for SEM

The steps for the preparation of sample for SEM are given below:

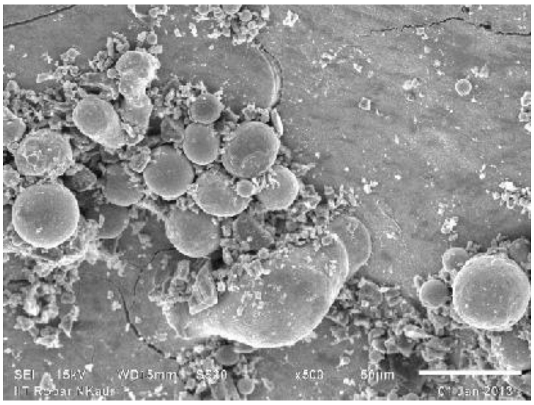
All the samples are cut into size of 10 X 12 mm

Clean the surface of sample with wire brush

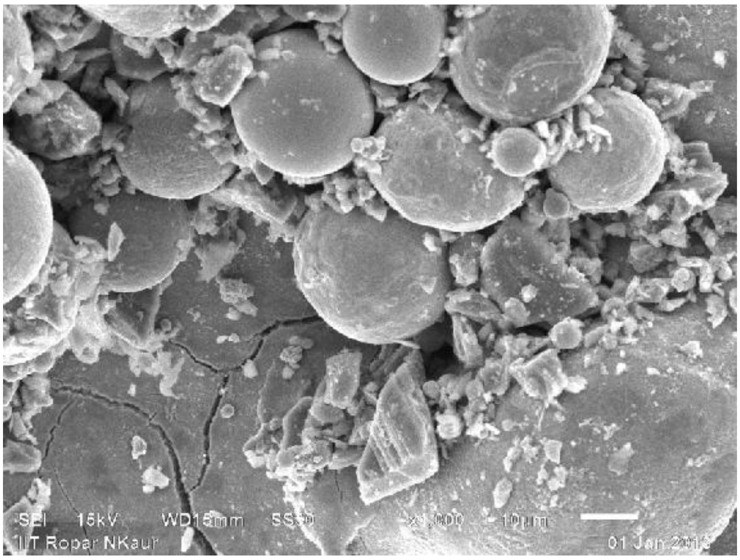
Clean the samples with acetone using cotton so as to remove debris from the machined surface.



(a) 200X



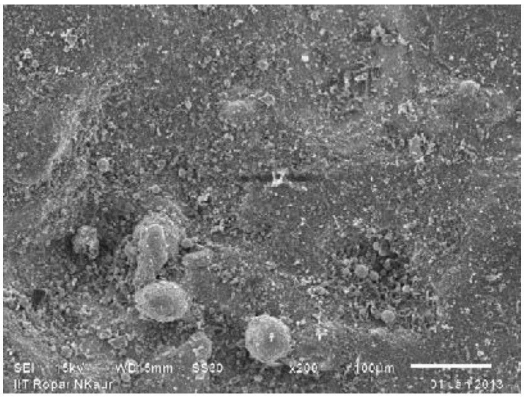
(b) 500X



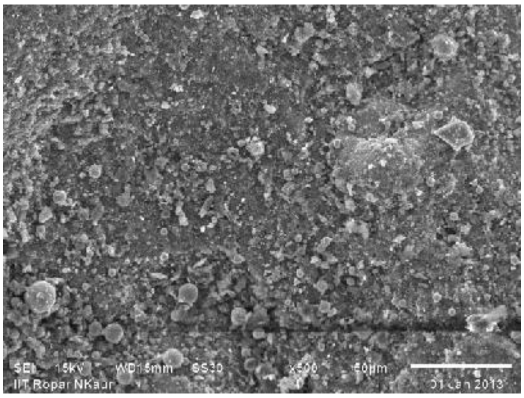
(c) 1000X

Figure 9.4: SEM micrograph of AISI 304 machined with 90° with Kerosene in Cu powder (I 5A, pulse on time 50 µs, concentration 15g/l)

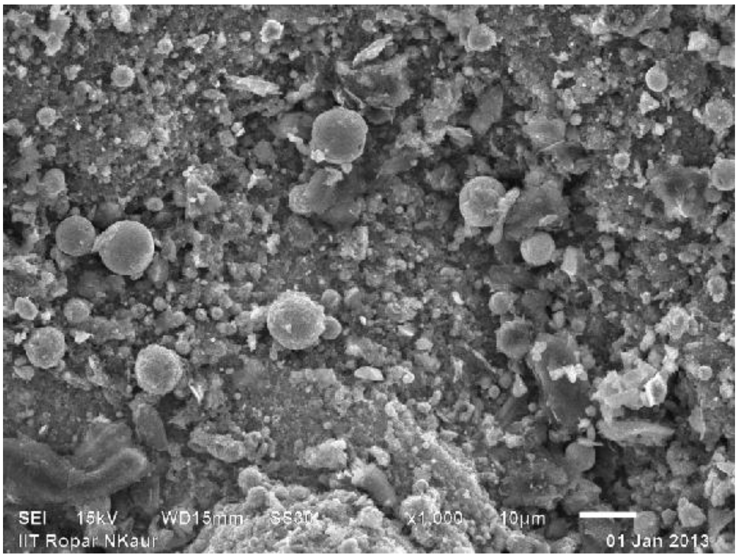
SEM micrograph at 200x, 500x and 1000x of AISI 304 machined with 90° with Kerosene in Cu powder (I 5A, pulse on time 50 µs, concentration 15g/l) are shown in Figure 9.4 which shows continuous formation of white layers one over another and cracks are present on the white layer. The reason for continuous formation of white layers is high peak current and pulse on time. This produces thermal stress due to white cracks occurs on the machined surface or it might be due to the large thickness of white layer. Presence of Chromium oxide (confirmed by XRD analysis) can also be the reason for cracks.



(a) 200X



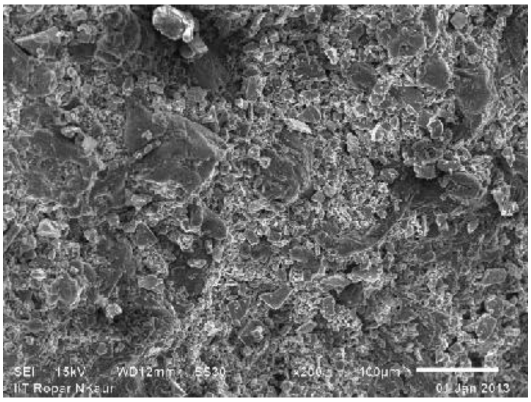
(b) 500X



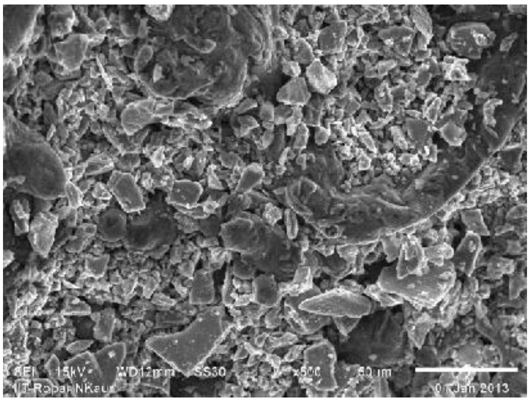
(c) 1000X

Figure 9.5: SEM micrograph of AISI 304 machined with 135° with Kerosene in Graphite powder (I 8A, pulse on time 100 µs, concentration 20g/l)

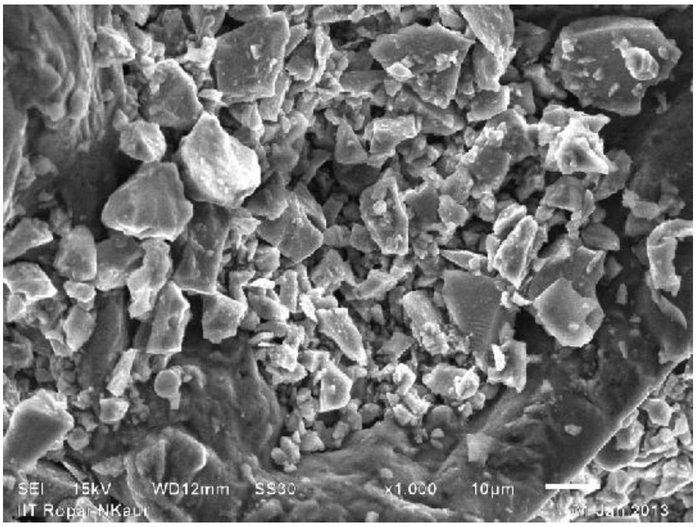
SEM micrograph at 200x, 500x and 1000x of AISI 304 machined with 135° with Kerosene in Graphite powder (I 8A, pulse on time 100 µs, concentration 20g/l) are shown in Figure 9.5 which shows the formation of craters. The result for creation of crater is uneven machining. There is a recast layer formed on the machined surface. The surface is rough because of debris which are not flashed away completely from the machined zone. High current and pulse on time has resulted in continuous formation of white layers. High peak current means more heat energy and high pulse on time means spark energy is continuously available for larger period of time. Hence, both the factors cause an impulsive force on the machined surface during sparking due to which materials are dispersed around the point where sparking takes place and thus white layers are formed.



(a) 200X



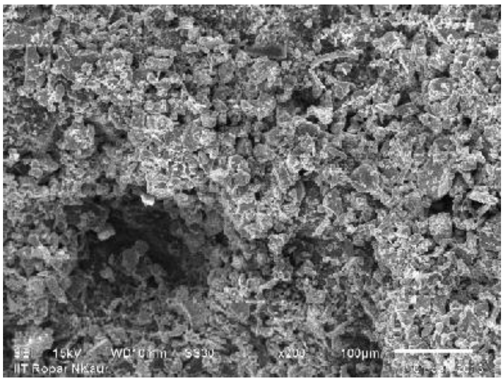
(b) 500X



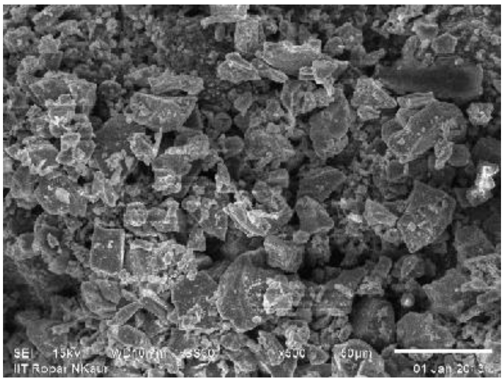
(c) 1000X

Figure 9.6: SEM micrograph of MMC machined with 135° with Kerosene in Si powder (I 8A, pulse on time 50 μs, concentration 10g/l)

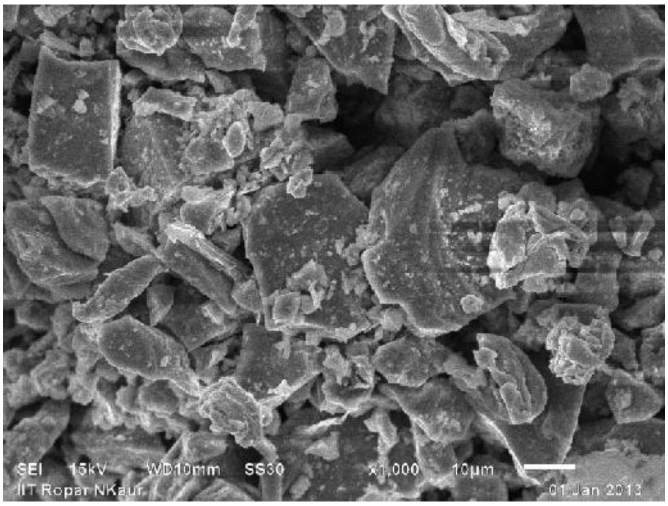
SEM micrograph at 200x, 500x and 1000x of MMC machined with 135° with Kerosene in Si powder (I 8A, pulse on time 50 μs, concentration 10g/l) are shown in Figure 9.6. It can be seen that the silicon carbide particles are distributed uniformly and well bonded with the aluminium matrix. The presence of silicon carbide particles in the microstructures could impede the movement of dislocations since these particles are stronger than the matrix in which they are embedded. The degree of strengthening produced also depends on the size of particles, their distance apart and the tenacity of the bond between particles and matrix. Since that the particles are stronger than the matrix, the dislocation cannot pass through them, but if the stress is high enough, the dislocation can by-pass them leaving a dislocation loop around each particle. This will make the passage of a second dislocation much more difficult, particularly since dislocations have greater difficulty in passing between particles which are near to each other.



(a) 200X



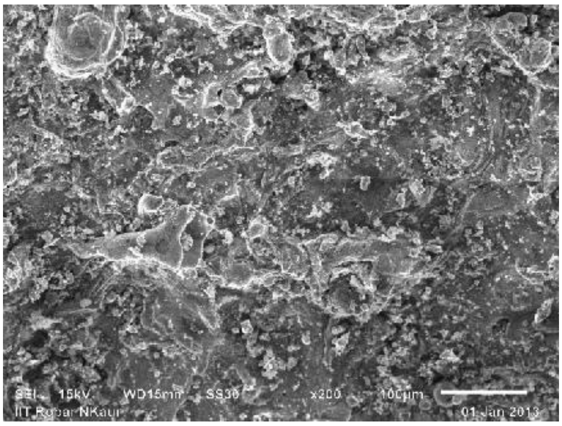
(b) 500X



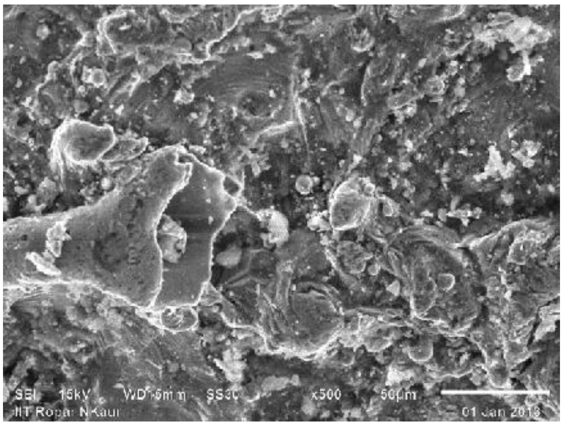
(c) 1000X

Figure 9.7: SEM micrograph of ALLOY machined with 45° with EDM Oil in Graphite powder (I 5A, pulse on time 10 µs, concentration 15g/l)

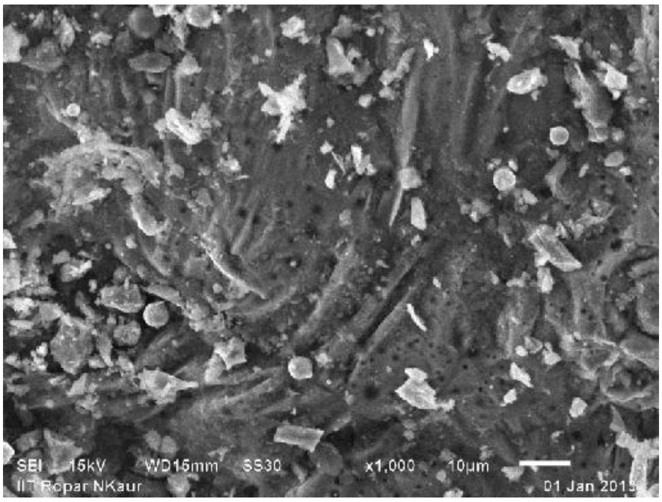
SEM micrograph at 200x, 500x and 1000x of ALLOY machined with 45° with EDM Oil in Graphite powder (I 5A, pulse on time 10 µs, concentration 15g/l) are shown in Figure 9.4.



(a) 200X



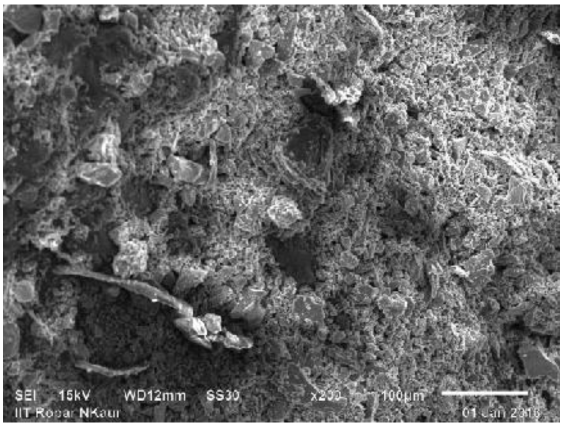
(b) 500X



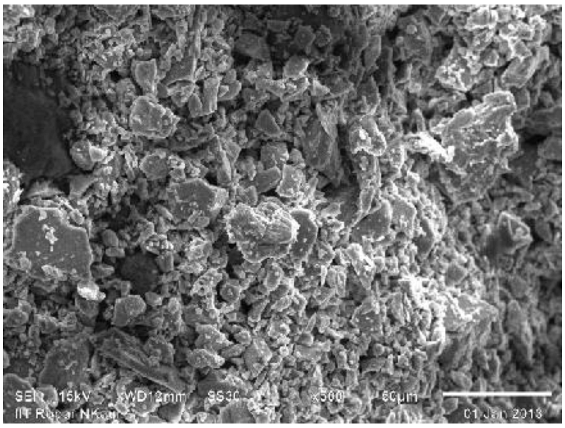
(c) 1000X

Figure 9.8: SEM micrograph of ALLOY machined with 135° with EDM Oil in Cu powder (I 5A, pulse on time 100 µs, concentration 10g/l)

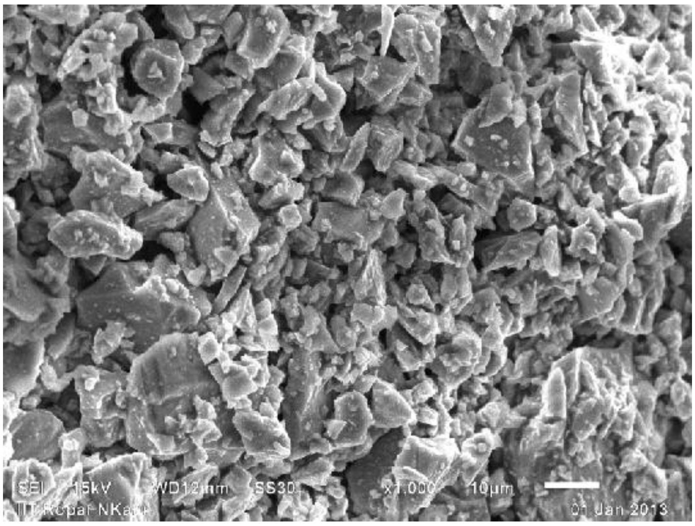
SEM micrograph at 200x, 500x and 1000x of ALLOY machined with 135° with EDM Oil in Cu powder (I 5A, pulse on time 100 µs, concentration 10g/l) are shown in Figure 9.5 shows inclusion which might have come due to melting of the material. White layer indicates that there might be grain boundary and plastic deformed porosity, which has non-uniform ductile dimples. SEM micrograph explains that, there is a chance that this material has low strength and brittle fracture.



(a) 200X



(b) 500X



(c) 1000X

Figure 9.9: SEM micrograph of MMC machined with 45° with EDM Oil in Si powder (I 5A, pulse on time 100 µs, concentration 20g/l)

SEM micrograph at 200x, 500x and 1000x of MMC machined with 45° with EDM Oil in Si powder (I 5A, pulse on time 100 µs, concentration 20g/l) shown in Figure 9.6 shows the cavities (craters) which got created due to electric discharges. This omnidirectional structure resembles point pattern, clear crater edges from melting and rapid solidification. As the EDM process is going on, the aluminium particles surrounded by the thick oxide film begin to increase in volume until the temperature at that point goes beyond the melting temperature of the aluminium, i.e. 6600C. The aluminium begin to melt and the volume of the aluminium particle increase then become large enough to break the oxide layer and make contact with the aluminium leaking from the neighbour particles. The melted aluminium also fills the voids between particles theoretically increasing density of the composite. The oxide smashed layers now exist in the form of small thin fragments scattered within the matrix preventing grain growth and dislocation movement and rising the melting temperature of the composites.

CHAPTER 10

RESULTS, ANALYSIS AND RECOMMENDATIONS

10.1 Results

The effects of parameters i.e. workpiece, dielectric, current, powder concentration, type of powder, pulse on time, angle were evaluated using ANOVA and factorial design analysis. The purpose of the ANOVA was to identify the parameters in prediction of MRR, TWR, Geometric Accuracy and Surface Roughness. Some results consolidated from ANOVA and plots are given below:

10.1.1 MRR

Pulse on time (F value 42.56) was found to be the most significant factor which contributes to MRR and its contribution was 37.67 % followed by Current (F value 37.14), Concentration (F value 10.38) and Powder type (F value 7.96) which had contribution to MRR was 32.63 %, 7.71% and 5.46 % respectively.

All the remaining factors were found to be insignificant in affecting the MRR.

For S/N ratio, current and pulse on time were found to be significant to MRR for reducing the variation.

Best values of MRR were suggested if workpiece is machined at 8 A current having Silicon powder with concentration of 20 g/l at pulse on time of 100 µs. With 95% confidence interval mean value of MRR was found to be 45.2887 $\pm$ 8.98 mm^3/min.

10.1.2 TWR

Concentration (F value 17) was found to be the most significant factor which contributes to TWR and its contribution was 29.34% followed by pulse on time (F value 16.57) and current(F value 14.86) which had contribution to TWR was 28.55% and 25.39% respectively.

All the remaining factors were found to be insignificant in affecting the TWR.

For S/N ratio, current and pulse on time were found to be significant to TWR for reducing the variation.

Best values of TWR were suggested if workpiece is machined with powder concentration of 10 g/l at 2 A current with pulse on time of 10 µs. With 95% confidence interval mean value of TWR was found to be 1.02 ± 0.68 mm^3/min.

10.1.3 WR

Workpiece Material (F value 8.77) was the only factor which contributes to WR and its contribution was found out to be 21.60%. All the factors were found insignificant.

For S/N ratio, concentration, current, angle and workpiece were found to be significant to WR for reducing the variation.

Best values of WR were suggested if MMC is machined at 2 A current at angle of 135° with powder concentration of 15 g/l. With 95% confidence interval mean value of WR was found to be 0.35 ± 0.05.

10.1.4 Geometric Accuracy

It is observed that the angle generated on the workpiece (Ø) is high when tool front angle is small and vice-versa. When the tool front angle is small then more variation occurs in sparking at different places between the tool and the workpiece and thus the angle generated on the workpiece is less accurate.

10.1.5 Surface Roughness (R_a)

It can be concluded that current and roughness have direct relationship. With the increase of current, the value of surface roughness increases. So, maximum roughness was found in case of 8 A and minimum for 2 A. So, for minimum value of roughness, 2 A current is a better choice. It can also be found that the evaluation length has created large effect in value of Surface Roughness. 0.25 mm has shown higher value of roughness while 0.08 mm has shown comparatively low roughness value. It is also clear from above table that high powder concentration gives low surface roughness. So, for best surface roughness, use powder concentration of 20 g/l. With the increase in pulse on time, the surface roughness increases. So, for best value of surface roughness, pulse on time of 10 µs is recommended.

10.1.6 XRD Analysis

XRD analysis was carried out on the three selected samples of different materials which cover all the parameters. XRD analysis of AISI 304 shows formation of oxides of Iron and Chromium. XRD analysis of MMC shows formation of Al_4C_3 and aluminium oxide. XRD analysis of ALLOY shows formation of $Cu_{15}Al_4$.

10.1.7 SEM Analysis

SEM micrograph was carried out on 6 selected samples at three different magnifications, namely at 200x, 500x and 1000x.The continuous formation of white layers one over another can be observed and cracks are present on these white layers. The reason for the continuous formation of white layers is high peak current and pulse on time. Both the factors cause an impulsive force on the machined surface during sparking due to which materials are dispersed around the point where sparking takes place and thus white layers are formed. These white layers are readily formed and it is stable on the surface. It is also observed that when current is increased, the crater size also increased.

10.2 Conclusions

The following conclusions were drawn from present study:-

1. The MRR are mainly affected by current, type of powder used, powder concentration and pulse on time.
2. The TWR are mainly affected by current, powder concentration and pulse on time.
3. The WR are mainly affected by workpiece material, angle of tool, powder concentration and current.
4. It can be concluded that when the tool front angle is small then more variation occurs in sparking at different places between the tool and the workpiece and thus the angle generated on the workpiece is less accurate. Similarly, when tool front angle is large, the angle generated between the tool and workpiece is more accurate.
5. It can be concluded that good surface roughness can be found at low value of current and low pulse on time and use powder concentration of high values.

10.3 Recommendations for Future Work

1. Only three workpiece materials namely Al-SiC composite, Al-Cu alloy and AISI 304 had been used. Other materials like Al-Si alloy, Al- ZrO_2 composite can be used.

2. Only three tool front angles (45°, 90° and 135°) were used. The effect of other tool front angles can also be studied.

3. Nickel and vanadium powders can be used and powder concentration can be varied to see its effects.

4. Effects can be seen by changing value of current, pulse on time and varying the values of pulse off time.

5. Dielectric fluid like Transformer oil can also be used.

APPENDIX-A

TECHNICAL SPECIFICATION OF EDM MACHINE

The experimentation has been conducted on Electrical Discharge Machine model T-3822M, Victory Electromech, Kolhapur, India. Technical data of machine is as under:

1. *Electrical Data*

Supply Voltage	415 V, 3Ø, 50 Hz
Connected Load	3 KVA
Open gap voltage output	135 ± 5% V
Max. Machine Current	12A
Current Range	3 ranges of 4 Amp each
Current Adjustment	0-4 Amp in each current range

2. *Machine Tool*

Height	300 mm
Width	730 mm
Depth	840 mm
Net weight	325 kg
Quill travel	150 mm

3. *Work Tank*

Length	600 mm
Width	350 mm

APPENDIX-B

SPECIFICATIONS OF DIELECTRIC MEDIUM

1. *Kerosene Oil*

Appearance	Clear, transparent, light
Density (kg/m^3)	817.28
Flash Point (°C)	40
Boiling Point (°C)	600
Viscosity (centistokes)	2.71

2. *EDM Oil*

Appearance	Clear, light
Density (kg/m^3)	835
Flash Point (°C)	130
Viscosity (centistokes)	3.12
Specific gravity	0.78 $\pm$ 0.04
Dielectric Strength	45 kv

APPENDIX-C

SPECIFICATIONS OF MEASURING INSTRUMENTS

1. PERTHOMETER

Make and model	Mahr, M4Pi, Germany
Measurement Method	Stylus
Profile resolution	100 nm
Cut-off length	0.8nm
Tracing length	4.8 mm

2. MICRO-HARDNESS TESTER

Make and Model	Metatech, MVH-2, Pune, India
Software used	Quantimet
Load	1 kg
Dwell time	20 sec

3. SCANNING ELECTRON MICROSCOPE

Make and Model	JSM-6610 LV, Jeol, Japan
Magnification	upto 3, 00,000x

4. X-RAY DIFFRACTION TESTER

Make and Model	ME 210 LA 2, Rigaku corporation
Scan speed	5°/minute

5. WEIGHTING MACHINE

Make	Shinko Densshi Co. Ltd, Japan.
Model	DJ, 300S.
Capacity	300 gram
Accuracy	0.01 gram

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