ELECTRICAL DISCHARGE MACHINING OF Cu-Al_2O_3 METAL MATRIX COMPOSITES

A THESIS SUBMITTED IN PARTIAL FULFILMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Mechanical Engineering

By

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Department of Mechanical Engineering

National Institute of Technology

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UNDER THE SUPERVISION OF

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Rourkela (India)

National Institute of Technology

Rourkela (India)

CERTIFICATE

This is to certify that thesis entitled, **"ELECTRICAL DISCHARGE MACHINING OF CU-Al_2O_3 METAL MATRIX COMPOSITES"** submitted by **Mr**. **VAIBHAV KUMAR AGNIHOTRI** in partial fulfillment of the requirements for the award of Master of Technology in Mechanical Engineering with "Production Engineering" Specialization during session 2014-2015 in the Department of Mechanical Engineering National Institute of Technology, Rourkela.

It is an authentic work carried out by him under my supervision and guidance. To the best of my knowledge, the matter embodied in this thesis has not been submitted to any other University/Institute for award of any Degree or Diploma.

Dr. Saurav Datta

Assistant Professor

Department of Mechanical Engineering

National Institute of Technology, Rourkela

Date: 27-05-2015

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VAIBHAV KUMAR AGNIHOTRI

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ABSTRACT

In today's scenario, MMCs are widely used in the manufacturing industries mainly in aerospace, automotive and electronics engineering due to its excellent mechanical and thermal properties as compared to conventional materials. But conventional machining process have been found difficulties in machining of these composites due to the due high tool wear, poor surface roughness, high machining cost etc. Hence, various researchers highlights the different advanced machining process such as electro discharge machining process, electro chemical machining process and electro or laser beam machining process in order to get effective machining for these composites. In this dissertation, EDM has been applied in order to machine Cu-Al_2O_3 metal matrix composite to obtain the high product quality with improved yield performance. Taguchi has been implemented to framework the layout of the experiment. The machining parameters such as current, voltage and pulse on time are taken whereas machining evaluation characteristics have been taken as material removal rate, tool wear rate and surface roughness. The work also adopted grey relation analysis to convert the aforesaid evaluation characteristics into a single response i.e. overall grey relation grade. Finally, Taguchi has been used to evaluate the optimal parametric combination.

Keywords: Cu-Al_2O_3, EDM, Taguchi analysis, grey relational analysis

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CHAPTER 1

Introduction

Composite material is a material composed of two or more physically and/or chemically distinct phases (matrix phase and reinforcing phase) and possessing bulk properties significantly different from those of any of the constituents. The composite normally has superior characteristics than those of each of the individual constituents. Most of the common materials (metals, alloys, doped ceramics and polymers mixed with additives) also have a small amount of scattered phases in their structures, however they are not considered as composite materials since their properties are similar to those of their base constituents (physical property of steel are similar to those of pure iron). Essential properties of composites materials include high stiffness and high strength, low density, high temperature stability, high electrical and thermal conductivity, adjustable coefficient of thermal expansion, corrosion resistance, improved wear resistance etc.

Matrix phase

- The primary phase, having a continuous character,
- Usually more ductile and less hard phase,
- Holds the reinforcing phase and shares a load with it.

Reinforcing phase

- Second phase (or phases) is imbedded in the matrix in a discontinuous form,
- Usually stronger than the matrix, therefore it is sometimes called reinforcing phase.

1.1. Types of metal matrix composites

Metal matrix composites are generally distinguished by characteristics of the reinforcement:

1. particle reinforced MMCs,
2. short fiber or whisker reinforced MMCs, and
3. Continuous fiber or layered MMCs.

The aspect ratio of the reinforcement is an important quantity, because the degree of load transfer from matrix to the reinforcement is directly proportional to the reinforcement aspect ratio. Thus, continuous fibers typically provide the highest degree of load transfer, because of very high aspect ratio, which results in a significant amount of strengthening along the fiber direction. Particle or short fiber reinforced metals have a much lower aspect ratio, so they exhibit lower strengths than their continuous fiber counterparts, although the properties of these composites are much more isotropic.

1.2. Applications of Metal Matrix Composites

- **Space:** The space shuttle uses boron/aluminium tubes to support its fuselage frame. In addition to decreasing the mass of the space shuttle by more than 145 kg, boron/aluminium also reduced the thermal insulation requirements because of its low thermal conductivity. The mast of the Hubble Telescope uses carbon-reinforced aluminium**.**

- **Military:** Precision components of missile guidance systems demand dimensional stability- that is; the geometries of the components cannot change during use. Metal matrix composites such as SiC/aluminium composites satisfy this requirement because they have high micro yield strength. In addition, the volume fraction of SiC can be varied to have a coefficient of thermal expansion compatible with other parts of the system assembly.

- **Transportation:** Metal matrix composites are finding use now in automotive engines that are lighter than their metal counterparts. Also, because of their high strength and low weight, metal matrix composites are the material of choice for gas turbine engines.MMCs are nowadays finding their use in automotive disc brakes. Early Lotus Elise models used aluminium MMC rotors, but they don’t possess better heat properties and Lotus has since switched back to cast-iron. Modern high-performance sport cars, such as those built by Porsche, use rotors made of carbon fiber within a silicon carbide matrix because of its high specific heat and thermal conductivity.

1.3. Processing of Metal Matrix Composites

Metal matrix composites can be processed using several methods. Few of them are described below:

1.3.1 Liquid state processes

- **Casting or liquid infiltration** involves infiltration of a fibrous or particulate reinforcement preform by a liquid metal. Liquid phase infiltration of MMCs is not straightforward, mainly because of difficulties with wetting the ceramic reinforcement by the molten metal. When the infiltration of a liquid preform occurs readily, the reactions between the fibre and the molten metal may take place which significantly degrade the properties of the fibre. Fibre coatings applied prior to infiltration, which improve wetting and allow control of interfacial reactions, have been developed and are producing encouraging results. In this case the disadvantage is that the fibre coatings must not be exposed to air prior to infiltration because surface oxidation of the coating takes place.

- **Squeeze casting or pressure infiltration** involves forcing a liquid metal into a fibrous or particulate preform. Pressure is applied until solidification is complete. By forcing the molten metal through small pores of the fibrous preform, this method obviates the requirement of good wettability of the reinforcement by the molten metal. Composites fabricated by this method have the advantage of minimal reaction between the reinforcement and the molten metal because of the short processing time involved. Such composites are typically free from casting defects such as porosity or shrinkage cavities.

1.3.2 Solid state processes:

- **Diffusion bonding** is a common solid state processing technique for joining similar or dissimilar metals. Interdiffusion of atoms between clean metallic surfaces, in contact at an elevated temperature leads to bonding. The principal advantages of this technique are the ability to process a wide variety of matrices and control of fibre orientation and volume fraction.

- **Deformation processing** can also be used to deform and densify the composite material. In metal composites mechanical processing of a ductile two phase material causes the two phases to co-deform, causing one of the phases to elongate and becomes fibrous in nature within the other phase. These metals are sometimes referred to as Insitu composites.

- **Powder processing** methods in conjunction with deformation processing are used to fabricate particulate or short fiber reinforced composites. This typically involves cold pressing or sintering, or hot pressing to fabricate primarily particle or whisker reinforced MMCs.

- **Sinter-forging** is a novel and low cost deformation processing technique. In sinter forging a powder mixture of reinforcement and matrix is cold compacted, sintered, and forged to nearly full density. The main advantage of this technique is that forging is conducted to produce a near net shape material, and machining operations and material waste are minimized. The low cost, sinter forged composites have tensile and fatique properties that are comparable to those of materials produced by extrusion.

- **Deposition techniques** for metal-matrix composite fabrication involve coating individual fibers in a tow with the matrix material needed to form the composite followed by diffusion bonding to form a consolidated composite plate or structural shape. The main disadvantage of using deposition techniques is that they are time consuming.

1.4 Electrical Discharge Machining

Electrical discharge machining (EDM) is a non-traditional concept of machining which has been widely used to produce dies and moulds. It is also used for finishing parts for aerospace and automotive industry and surgical components [1]. This technique has been developed in the late 1940s [2] where the process is based on removing material from a part by means of a series of repeated electrical discharges between tool called the electrode and the work piece in the presence of a dielectric fluid [3]. The electrode is moved toward the work piece until the gap is small enough so that the impressed voltage is great enough to ionize the dielectric [4]. Short duration discharges are generated in a liquid dielectric gap, which separates tool and work piece. The material is removed with the erosive effect of the electrical discharges from tool and work piece [5]. EDM does not make direct contact between the electrode and the work piece where it can eliminate mechanical stresses, chatter and vibration problems during machining [1]. Materials of any hardness can be cut as long as the material can conduct electricity [6]. EDM techniques have developed in many areas. Trends on activities carried out by researchers depend on the interest of the researchers and the availability of the technology. In a book published in 1994, Rajurkar [7] has indicated some future trends activities in EDM: machining advanced materials, mirror surface finish using powder additives, ultrasonic-assisted EDM and control and automation.

1.5 EDM Principle

Electrical discharge machining (EDM), otherwise known as thermal erosion process, is one of the non-conventional machining processes, where tool and workpiece do not come into contact with each other during the machining process. The progression of events constituting the process of material erosion from the work surfaces by an electrical discharge machining can be explained in the following way. If an appropriate voltage is developed across the tool electrode (normally cathode) and the workpiece (normally anode), the breakdown of dielectric medium between them happens due to the growth of a strong electrostatic field. Owing to the electric field, electrons are emitted from the cathode toward the anode on the electrode surfaces having the shortest distance between them. These electrons impinge on the dielectric molecules of the insulating medium, breaking these dielectric fluid molecules into positive ions and electrons. These secondary electrons travel along on the same ionization path. This event causes an increase in the electric field strength across the work surfaces and liberates a large number of electrons. It creates an ionized column in the shortest spark gap between the tool electrode and the workpiece, thereby decreasing the resistance of the fluid column and causing an electrical discharge in the shortest distance point between the tool and the workpiece. The enormous thermal energy melts and vaporizes the material from the workpiece, which creates a small crater over the work surface. There happened a collapse of the ionized column with the termination of the electrical energy by means of the switching circuit and then surrounding dielectric fluid occupies its place. The melted debris is removed by the flushing process. The conduction of dielectric medium can be determined by the current, duration and pulse energy [1]. Fig. 1 explains the formation of ionized column in the shortest distance of work surfaces using the EDM process [1].

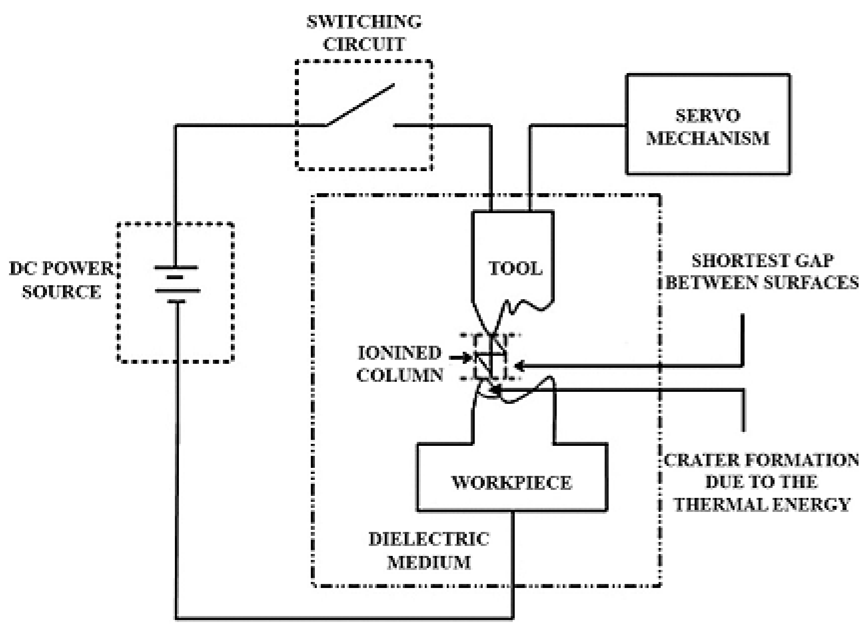


Fig. 1 Basic mechanism involved in EDM.

1.6 Important parameters of EDM

a) **Open-circuit Voltage**: Open-circuit voltage specifies the voltage of applied pulses. It is not the voltage across the gap during electrical discharges.

b) **Discharge Current**: Current is measured in ampere per cycle. Discharge current is directly proportional to the Material removal rate.

c**) Duty Factor**: It is a percentage of the on-time relative to the total cycle time. This parameter is calculated by dividing the on-time by the total cycle time (on-time pulse off time).

$$\tau = \frac{t_{on}}{t_{on} + t_{off}}$$

d) **On-time (pulse time or t_i):** It is the duration of time for which the current is allowed to flow per cycle. Material removal is directly proportional to the amount of energy applied during this on-time. This energy is controlled by the peak current and the length of the on-time.

e) **Off-time (pause time or t_0):** It is the duration of time between the sparks (Ton). This time allows the molten material to solidify and to be wash out of the arc gap. This parameter affects the speed and the stability of the cut. Thus, if the off-time is too short, it will cause unstable sparks.

f) **Arc gap (or gap)**: It is the distance between the electrode and the part during the process of EDM. It may be called as spark gap.

g) **Diameter of electrode (D)**: It is the electrode of Cu-tube there are two different size of diameter 4mm and 6mm in this experiment. This tool is used not only as an electrode but also for internal flushing.

1.7 Advantages of Electric Discharge Machining (EDM)

There are a lot of benefits when using electrical discharge machine (EDM) when machining. This is due to its capabilities and advantage. To summarize, these are the electric discharge machine (EDM) capabilities compare to other method:

• Material of any hardness can be cut

• High accuracy and good surface finish are possible

• No cutting forces involved

• Intricate-shaped cavities can be cut with modest tooling costs

• Holes completed in one “pass”

1.8 Limitations of Electric Discharge Machining (EDM)

Few limitations of electrical discharge machining (EDM) are:

• Limited to electrically conductive materials

• Slow process, particularly if good surface finish and high accuracy are required

• Dielectric vapour can be dangerous

• Heat Affected Zone (HAZ) near cutting edges

• Die sinking tool life is limited.

1.9 Applications of EDM:

(a) In the machining of very hard metals and alloys used in aerospace, automotive and nuclear industries.

(b) It is a promising technique to meet increasing demands for smaller components usually highly complicated, multi-functional parts used in the field of micro-electronics.

(c) Application potential of EDM can be further enhanced if its machining rates can be increased and resulting surface damage to the work piece is accurately estimated and reduced.

(d). It is used to machine extremely hard materials that are difficult to machine like alloys, tool steels, tungsten carbides etc.

(e). It is used in forging, extrusion, wire drawing, thread cutting.

(f). It is used for drilling of curved holes.

(g). It is used for machining sharp edges and corners that cannot be machined effectively by other machining processes.

Literature review

Rosso [8] discussed that metal matrix composites have a number of advantageous properties as compared to monolithic metals including higher specific strength, higher specific modulus, and resistance to elevated temperatures, better wear resistance and lower coefficients of thermal expansion. **Lindroos and Talvitie [9]** showed that in past two decades, metal matrix composites have been generating broad range of research fraternity in material science. Major of the applications and works have been demanding aluminium and other light matrices for purposes desiring high strength and accuracy along with light weight. **Clyne [10]** proposed that advantages in some attributes of MMCs such as no significant moisture absorption properties, non-inflammability, low electrical and thermal conductivities and resistance to most radiations.

Jianhua et al. [11] proposed that the increase in reinforcement content in the matrix increases the wear resistance of the composite material. **Eckert et al. [12]** gave the view that the main advantage of P/M over other methods, such as liquid and vapour state processing, is the relatively low processing temperature, which may avoid undesired interfacial reactions between matrix and reinforcement. **Procio et al. [13]** found that the conventional powder metallurgy route for fabrication of involves proper blending or mixing of appropriate weight percentage of powders to obtain a homogenous mixture, cold uniaxial compaction for obtaining green sample, sintering at appropriate sintering temperature and finally heat treatment like ice quenching and ageing for enhancing various mechanical properties.

Berghezan [14] found that the composites are compound materials which differ from alloys by the fact that the individual components retain their characteristics but are so incorporated into the composite as to take advantage only of their attributes and not of their shortcomings. **Dasgupta [15]** found that aluminium alloy-based metal matrix composites (AMMCs) have been now proved themselves as a most acceptable wear resistant material especially for sliding wear applications.

Efe et al.[16] proposed that copper is an excellent material for electrical applications whose efficiency can be enhanced by improving its mechanical properties. **Motto et al. [17]**

found that when alumina particles are dispersed in copper matrix, they exhibit unique characteristics, such as high thermal and electrical conductivity, as well as high strength and excellent resistance to annealing.

Gangadhar et al. [18] investigated the performance of Cr/Cu-based composite electrodes. The results showed that using such electrodes facilitated the formation of a modified surface layer on the work piece after EDM, with remarkable corrosion resistant properties. The optimal mixing ratio, appropriate pressure, and proper machining parameters (such as polarity, peak current, and pulse duration) were used to investigate the effect of the material removal rate (MRR), electrode wear rate (EWR), surface roughness, and thickness of the recast layer on the usability of these electrodes. According to the experimental results, a mixing ratio of Cu–0wt%Cr and a sinter pressure of 20 MPa obtained an excellent MRR.

Hassann et al. [19] found that owing to their lower density and better mechanical properties, nowadays, magnesium-based composites are becoming potential candidate materials for automotive and aerospace applications. Technology of magnesium-based composites is in the developing stage. Although magnesium is a relatively softer material, magnesium-based metal matrix composites are difficult to be machined.

Gary et al. [20] found that Electric discharge machining (EDM) is one of the non traditional machining techniques which is widely used to machine harder materials. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage for manufacturing of mould, die, automotive, aerospace and surgical components.

Karthikeyan et al. [21] proposed that in EDM machining of aluminium composite reinforced with micron-sized particles of SiC, the discharge is more irregular and larger current is necessitated. EDM drilling with rotary tubular electrode normally results in increased material removal rate (MRR), lower electrode wear rate (EWR) and improved surface finish.

Biing et al. [22] identified Open gap voltage and pulse-on time as significant influencing parameters on material removal rate in wire-cut EDM of aluminium composites. Increase in the volume fraction of alumina reinforcement poses problems during machining. The interruption to machining is caused by the embedded alumina particles.

Mohan et al. [23] said that MRR, EWR, and surface roughness (SR) are considered for evaluating machinability of aluminium silicon carbide composites. Pulse duration has an inverse effect on all response variables such as MRR, EWR, and SR.

Mahdavinejad [24] aimed to optimize electro discharge machining parameter for WC-Co work piece material and copper electrode using the neural model predictive control method. The testing results from ED machining of WC-Co confirms the capability of the system of predictive controller model based on neural network with 32.8% efficiency increasing in stock removal rate. **Sundaram et al. [25]** experimentally studied the performance of copper-graphite as tool material in micromachining by micro electro discharge machining.

Saha and Choudhury [26] studied the process of dry EDM with tubular copper tool electrode and mild steel workpiece. Experiments have been conducted using air and study the effect of gap Voltage, discharge current, pulse-on time, duty factor, air pressure and spindle speed on MRR, surface roughness (Ra) and TWR. Empirical models for MRR, Ra and TWR have then been developed by performing a designed experiment based on the central composite design of experiments. **Rebelo et al. [27]** presented an experimental study on the effect of EDM parameters on material removal rate (MRR) and surface quality, when machining high strength copper-beryllium alloys. Processing parameters for rough, finishing and micro-finishing or polishing regimes were analyzed.

Patel et al. [28] presented an erosion model for anode material. The model accepts power rather than temperature as boundary condition at plasma/anode interface. A constant fraction of the total power supplied to the gap is transferred to the anode. The power supplied is assumed to produce a Gaussian-distributed heat flux on the area of anode which grows with time. Rapid melting of anodic material and subsequent resolidification of the material for longer durations of time is presented.

Yadav et al. [29] proposed that the high temperature gradients generated at the gap during EDM result in large localized thermal stresses in a small heat-affected zone leading to micro-cracks, decrease in strength and fatigue life and possibly catastrophic failure. A finite element model has been developed to estimate the temperature field and thermal stresses. **Allen et al. [30]** presented the process simulation and residual stress analysis for the micro-EDM machining on molybdenum. Material removal is analyzed using a thermo-numerical model, which simulates a single spark discharge process. Using the numerical model, the effects of important EDM parameters such as the pulse duration on the crater dimension and the tool wear percentage are studied.

Lauwers et al. [31] presents a detailed investigation of the material removal mechanisms of some commercially available electrical conductive ceramic materials through analysis of the debris and the surface/sub-surface quality. ZrO2-based, Si3N4-based and Al2O3-based ceramic materials, with additions of electrical conductive phases like TiN and TiCN, have been studied. They pointed out that besides the typical EDM material removal mechanisms, such as melting/evaporation and spalling, other mechanisms can occur such as oxidation and dissolution of the base material. The formation of cracks depends among factors like thermal conductivity of the material, melting point and strength, on the fracture toughness of the material.

Madhu et al. **[32]** proposed a model for predicting the material removal rate and depth of damaged layer during EDM. The transient heat conduction equation for the work piece which accounts for the heat absorption due to melting has been solved by Finite Element Method. Simulations have been performed for a single spark in the form of pulses. The width of crater and the depth of penetration depend on spark-radius and the power intensity. It was found that MRR increases with power per spark and decreases with an increase in computational machining cycle time. It increases immediately after machining starts but soon reaches a steady state value.

Zhang et al. [33] proposed an empirical model, built on both peak current and pulse duration, for the machining of ceramics. It was realized that the discharge current has a greater effect on the MRR; while the pulse-on time has more influence on the SR and white layer.

Lin et al. [34] has reported that Electrical Discharge Energy on Machining of Cemented Tungsten Carbide using an electrolytic copper electrode. The machining parameters of EDM were varied to explore the effects of electrical discharge energy on the machining characteristics, such as MRR, EWR, and surface roughness. Moreover, the effects of the electrical discharge energy on heat-affected layers, surface cracks and machining debris were also determined. The experimental results show that the MRR increased with the density of the electrical discharge energy.

Zhon et al. [35] worked on servo system for EDM, adaptive control with self turning regulator a new EDM adaptive control system which directly and automatically regulates tool down-time has been developed. Based on the real-time-estimated parameters of the EDM process model, by using minimum-variance control strategy, the process controller, a self-tuning regulator, was designed to control the machining process so that the gap states follow the specified gap state. With a properly selected specified gap states, this adaptive system improves the machining rate by, approximately, 100% and in the meantime achieves a more robust and stable machining than the normal machining without adaptive control. This adaptive control system helps to gain the expected goal of an optimal machining performance.

Kumar et al.[36] used Taguchi's L27orthogonal array and conducted experiments to study the effect of various parameters like applied voltage, electrolyte concentration, feed rate and percentage reinforcement on maximizing the material removal rate and developed a mathematical model using the regression method.

Goswami [37] studied the effect of electrolyte concentration, supply voltage, depth of cut, and electrolyte flow rate on the evaluation of material removal rate (MRR), surface finish, and cutting forces during electrochemical grinding of Al_2O_3/Al interpenetrating phase composite using Taguchi based design.

Rao and Padmanabhan [38] employed Taguchi Methods, the Analysis of Variance (ANOVA), and regression analyses to find the optimal process parameter levels and to analyze the effect of these parameters on metal removal rate values in electrochemical machining of LM6 Al/5%SiC composites.

2.1 Objective of the present work

It has been revealed from the literature that less work has been carried out in machining of Cu-Al_2O_3 composite. Hence, this present dissertation comprises of two parts: First parts highlights the fabrication of Cu-Al_2O_3 by powder metallurgy technique and later part describes the machining of these composites in EDM. The study also used the grey relation analysis integrated with Taguchi technique in order to assess the favourable machining condition.

Experimentation

3.1 Fabrication of composites:

Cu-Al_2O_3 has been fabricated by using powder metallurgy process. Following are the steps involved in powder metallurgy

3.1.1. Mixing of powders

Copper powders were mixed with alumina particles to form a mechanical mixture of Cu-alumina powder comprising 90% of Cu powder and 10% of Al_2O_3 powder by weight to form a composite of 15 gram each. Blending of powders was accomplished in ball planetary mill (Model-PULVERISETTE-5, Make-FRITSCH, Germany) shown in Fig 3.1. It consisted of three cylindrical containers made up of chrome steel within which 10 balls made up of chrome steel of sizes 10 mm. To achieve a homogenous distribution of the reinforcement in the mixture the blending machine was set up for 2 Lakh revolutions.

Fig 3.1: Ball Planetary Mill

3.1.2. Weighing of samples

Mixing was followed by weighing the samples in an electronic weighing machine. Batch of nine samples were prepared keeping the weight of each of them as 10 grams.

Fig 3.2: Electronic weighing machine

3.1.3 Compaction of powder

After carrying out the blending operation, pressing operation was performed at room temperature in a die punch arrangement made up of stainless steel at pressures which make the powders stick to each other. This process is called cold compaction. Cold isostatic pressing was used for compacting the blended powders into a 'green compact form', with appropriate density. About 10 gm of the powder mixture was taken adopting a method of coning and quartering for compaction.

3.1.4. Cold uniaxial press

For each component, approximately 10 gm of powder was measured out and poured into the die cavity. The equipment used for this machine is cold uniaxial pressing machine (Make - SOILLAB, Type-Hydraulic, Maximum load: 20 tonne) as shown in Fig. 3.3. To fabricate the green circular test samples of 25 mm outer diameter a load of 5 ton was applied, which yielded 1018 bar pressure. For this purpose, a stainless steel die of 25 mm internal diameter was used. To prevent the specimen from sticking on to the walls and to allow the powder to flow freely, acetone was applied to the walls of the die and punch as lubricant. The die body was split, with slight pressure applied to the green component and both sides of the die were pulled from the component. The pressure on the component was then released completely, the top punch was removed and the component was ejected by downward movement of the floating die body.

Fig 3.3: Cold Uniaxial Pressing Machine

3.1.5. Sintering

Sintering operation was carried out in a horizontal tubular furnace (Make-Naskar and Co., Type-Vacuum and Control Atmosphere, Maximum temperature: 1600^0C, Cooling rate: 5^0C/min.) The samples were baked in a controlled atmosphere of argon at a pressure of 1 bar, temperature of 620^0 C and a holding time of one hour. The aluminium particle was always surrounded by an oxide layer. The oxide layer fragmented into small shell pieces disrupted in the copper matrix restrains the increment in strength and the movement of dislocation. Then furnace was left to cool to room temperature for a time period of 24 hours. Then, the pallets were taken out of the furnace and kept in desiccators which contained concentrated H_2SO_4. The average thickness and diameter of pallets are 5 mm and 25 mm respectively.

Fig. 3.4: Horizontal Tubular Furnace **Fig. 3.5:** Samples after sintering

3.1.6. Quenching

After sintering the samples were then solution heat treated in a heat treatment furnace (local made) as shown in Fig. 3.6. Quenching was carried out at a temperature of 500 ^{0}C for a span of one hour and then quenched in iced water.

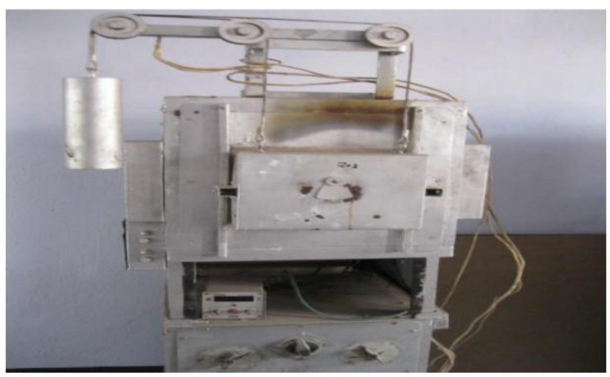


Fig. 3.6: Heat Treatment Furnace

3.1.7. Ageing

After quenching operation, there is initiation of natural ageing in the composites. In order to prevent it, all the quenched samples were artificially aged immediately after solution heat treatment. The ageing operation was carried out in a closed muffle furnace as shown in Fig. 3.7. All samples were aged at temperature of 200^{0}C for span of eight hour and allowed to cool in it to room temperature.

Fig. 3.7: Closed Muffle Furnace

3.2 SEM Analysis

The microstructures of samples are studied using a Scanning Electron Microscope (SEM) (JEOL JSM 6480 LV) shown in Figure 3.8:-

Fig. 3.8: Scanning Electron Microscope apparatus

Specifications:

- High-vacuum mode (HV mode)

I. Resolution (SEI) :- 3.0 nm guaranteed (Acc V 30kV , WD 8mm)

II. Magnification :- 8 x (WD 46mm) to 300,000 x (146 steps, digital indication)

III. Image mode :- SEI, BEI (composition image, topographic image and stereoscopic image)

IV. Probe current: - approximately 1pA to 1µA.

- Low vacuum mode (LV mode)

I. Resolution (BEI) :- 4.0 nm guaranteed (Acc V 30kV , WD 5mm)

II. Vacuum pressure in the specimen chamber

III. Adjustable pressure:- 10 to 270 Pa

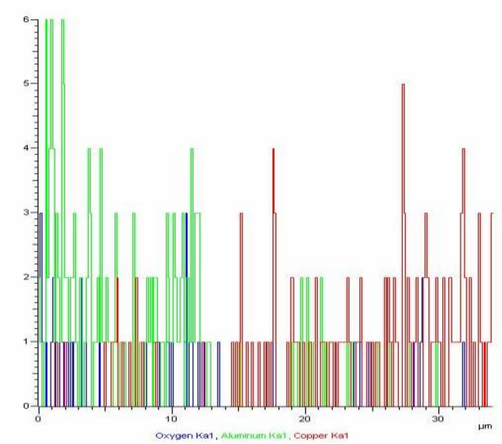
IV. Lowest pressure :- 1 Pa

V. Image mode :- SEI, BEI (composition image, topographic image and stereoscopic image)

Note:-

SEI: - Secondary electron image, BEI: - Backscattered electron image, Acc V: - Accelerating Voltage, WD: - Work distance

The microstructures obtained by scanning electron microscopy (SEM) give ample information about the pore density, distribution, alignment and nature of pores along with the matrix reinforcement bonding. Fig depict microstructures of Cu-Al_2O_3 MMC, where white patches correspond to alumina and the grey area referring to the copper matrix. The reason behind the white colour of alumina particles is that alumina being a non conductor of electricity does not allow the electrons striking during X-ray emission to penetrate inside the particle and therefore charging takes place at the surface and charge gets deposited on the surface. On the other hand, Copper being a good conductor allows the flow of electrons the surface of the copper particle to penetrate inside and finally are discharged to earth. Distortion in the figure arises due to charging. Therefore figure is not clear and some blurr can be noticed.



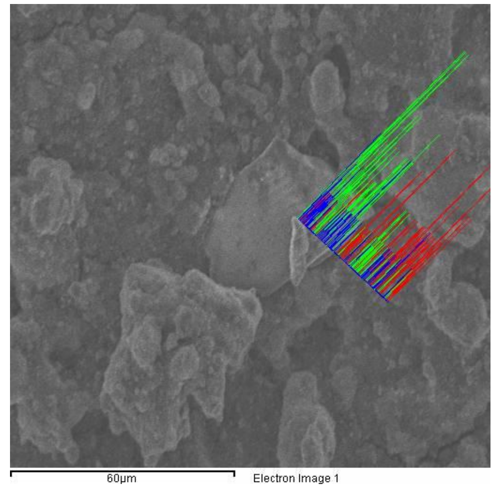


Fig 3.9: Representation of various elements in Line graph

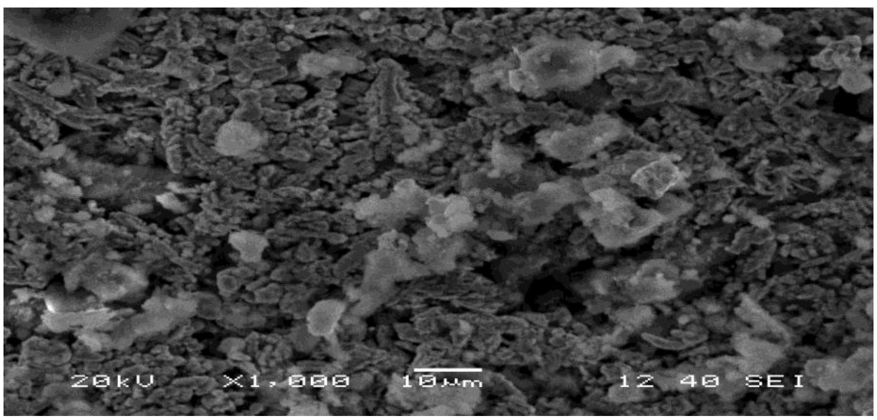


Fig 3.10: SEM Micrograph revealing microstructure of Copper and alumina

3.2.1. EDS Analysis

Energy dispersive X-ray spectroscopy analysis can be defined as a technique used for the chemical characterization of a sample. It depends on some source of X-ray excitation and a specimen. To encourage the emission of X-rays from a sample a very high energy beam of charged particles (such as electrons and protons) are directed on the sample. While at rest atoms present inside the sample contain electrons at the ground level. The incident beam may excite an electron present in an inner shell, ejecting it from the shell while creating a hole due to electron vacancy. An electron from an outer, higher-energy shell then fills this hole, and the difference in energy between the higher-energy shell and the lower energy shell may be released in the form of an X-ray. The number and energy of the X-rays emitted from a specimen can be measured directly by an energy-dispersive spectrometer.

In this analysis we take a small portion over individual particles (for e.g. alumina) and then determine the individual percentage of the different constituents present in the particles. For eg: Al-44%, O-56% or Cu-99%, Fe-1%. In the first instance we have projected X-rays onto the area shown by spectrum 2 it is basically black portion which consists mainly of copper and small traces of iron, aluminium and the analysis performed confirms the fact that the area consists of copper as the major element. Similarly we performed this analysis on the area depicted by grey colour. In this way we were able to predict the amount and composition of the various elements present in the given sample and the results were in conformity with the actual results.

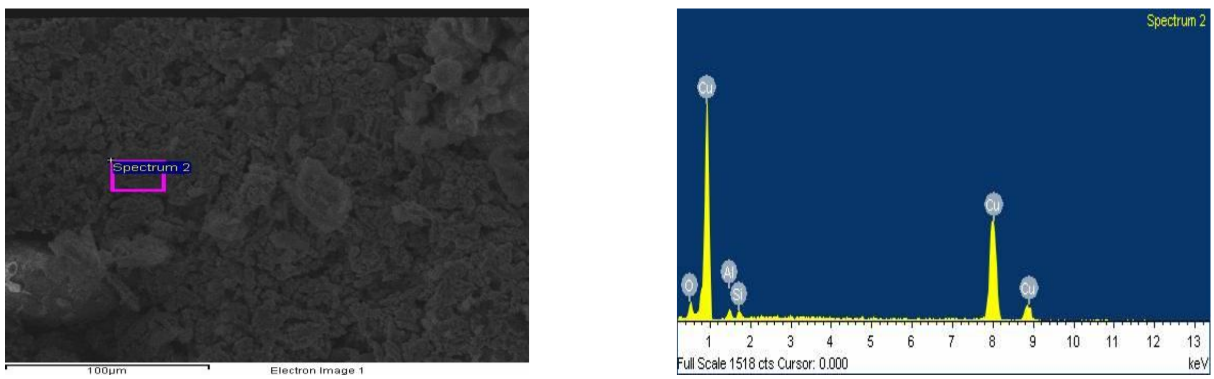


Fig 3.11: EDS Analysis performed by taking a point on the grey portion showing electron energy level against number of counts

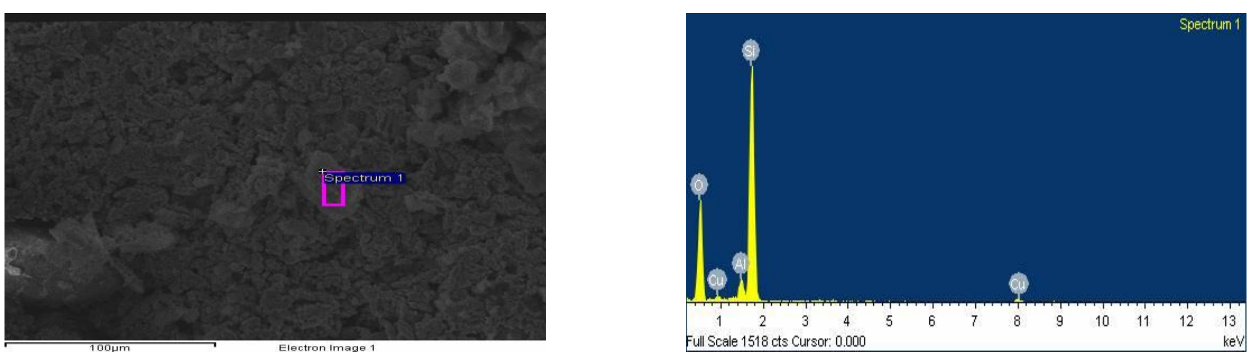


Fig 3.12: EDS Analysis performed by taking a point on the white portion showing electron energy level against number of counts

3.3 Electro Discharge Machining

This thesis is aimed to evaluate the optimal machining condition in EDM of Cu-Al_2O_3 composites. Experimentation has been carried out on EDM machine (PS50 ZNC) installed at Production laboratory of Mechanical Engineering Department, NIT Rourkela, India which is shown in Fig. 1.

Fig 3.13: Electro discharge machine

3.4 Tool Material and Work Material

In this experiment, the Copper U-shaped tool with internal flushing system has been used as tool material. 9 samples of Cu-Al_2O_3 composites have been used as work-piece material.

Fig. 3.14: Electrode and work piece material used in the experiment

3.5 Calculations: **Density calculation for composite**

- **Actual density of composite sample**

$$\rho_c = \frac{M_C}{V_C} \qquad \textbf{(3.1)}$$

M_C = Mass of composite (9.27 gm)

V_C = Volume of composite

$$V_C = \frac{\Pi}{4} \times d^2 \times t \qquad \textbf{(3.2)}$$

d = dia. of sample = 25 mm

t = Thickness of sample = 5 mm

After calculation we get ρ_c = 3.777×10^{-3} gm/ mm^3

ρ_c = density of composite material

- **Theoretical Density of composite material (by weight percentage)**

$$\frac{1}{\rho_C} = \frac{W_F}{\rho_F} + \frac{W_M}{\rho_M} \quad \textbf{(3.3)}$$

W_F = Weight fraction of aluminium oxide (0.1),

ρ_M = Density of copper (8.96×10^{-3} gm/ mm^3)

W_M = Weight fraction of Copper (0.9)

ρ_F = Density of aluminium oxide (3.95×10^{-3} gm/ mm^3)

F- fibre material, *M*- matrix material

After calculation density of composite material – 7.95×10^{-3} gm/mm^3

- **Density of tool**

ρ_{cu} = 8.96×10^{-3} gm/ mm^3

3.6 Design of Experiment (DOE)

Design of Experiment consists of systematically layout for the each experimental run. Taguchi's orthogonal array design of experiment has been selected for the framework of DOE as it minimizes the experimental run which saves times and cost of the experimentation. In this present study, three machining parameter have been varied into three different levels which are shown in Table 3.1. Here, L9 orthogonal array has been chosen for experimentation which are presented in Table 3.2.

Table 3.1: Input factors and their levels

Factors	Units	Level 1	Level 2	Level 3
Current (Ip)	Amp	7	8	9
Voltage (V)	Volt	70	80	90
Pulse on time	Us	75	100	150

Table 3.2: Design of experiment

Sl. No.	Current (A)	Voltage	Pulse on time
1.	7	70	75
2.	7	80	100
3.	7	90	150
4.	8	70	100
5.	8	80	150
6.	8	90	75
7.	9	70	150
8.	9	80	75
9.	9	90	100

3.7 Performance Parameters

Material Removal Rate (MRR), Tool wear rate (TWR) and surface roughness have been used for assessing machining performance characteristics.

MRR is calculated using the volume loss of the work piece material as cubic millimeter per minute(mm^3/min).The weight loss i.e. difference between the weight of work piece before machining and the weight of the work piece after machining is measured by an electronic balance weight measuring machine (Sansui (Vibra), Shinko Denshi Co. Ltd. Made in Japan) with a least count of 0.001 gm. MRR has been computed as below:

$$MRR = \frac{(W_i - W_f)}{(\rho_c \times T)} \qquad \textbf{(3.4)}$$

Whereas, W_i = Initial weight of work piece, W_f = Final weight of work piece, ρ_c = Density of composite, T = Time of machining

TWR is calculated using the volume loss of the Tool material as cubic millimeter per minute(mm3/min).The weight loss is measured by an electronic balance weight measuring machine (Sansui (Vibra), Shinko Denshi Co. Ltd. Made in Japan) with a least count of 0.001 gm.

$$TWR = \frac{(T_i - T_f)}{(\rho_t \times T)} \quad \textbf{(3.5)}$$

T_i = Initial weight of tool, T_f = Final weight of tool, ρ_t = Density of tool, T = Time of machining

The measurement of the surface profiles of the EDM specimens utilize a portable stylus type profilometer like Talysurf (Taylor Hobson). It is based on carrier modulating principle and has a stylus which skids over the surface to measure the roughness.

Fig 3.15: Portable Stylus Type Profilometer like Talysurf

3.8 Taguchi Analysis:

Taguchi method is a statistical method developed by Dr. Genichi Taguchi to improve the quality of manufactured goods [39]. Professional statisticians have welcomed the goals and improvements brought about by Taguchi methods, particularly by Taguchi's development of designs for studying variation in the output from targeted value. However, the method is criticized due to inability to solve multi-objective optimization proposals. In order to overcome this, utility theory, grey relation theory desirability function approaches have been reported and well documented in literature. These are widely being applied in combination with Taguchi method.

Hussain et al. [40] suggested that productivity and quality are the two important aspects of machining process. Surface roughness and material removal rate greatly influence the performance of mechanical parts and the production cost. So, quality and productivity is to be monitored simultaneously at every stage and actions are to be taken in case of deviation from the target.

Taguchi method is very commonly used in product/ process design optimization. This method explores the concept of (Signal-to-Noise) S/N ratio to optimize the given process control parameters with respect to an objective function (called response) via reduction in variances. The characteristic that the higher value represents better machining performance, such as metal removal rate (Vw), is called “higher is better, HB“. Inversely, LB stands for “lower is better”, such as surface roughness. The S/N ratio (signal-to-noise ratio, η) is an effective representation to find significant parameters by evaluating minimum variance. For HB and LB, the definition of S/N ratio for machining performance y_i of n repeated number (in this case n=3, i=1,2,3) are computed as:

Type1- $S / N_{HB} = -10 \log[(\frac{1}{n})(\sum \frac{1}{y_{ij}^2})]$ **(3.6)**

Type 2- $S / N_{LB} = -10 \log[(\frac{1}{n})(\sum y_{ij}^2)]$ **(3.7)**

4.1 Grey Relational analysis

The grey system theory was initiated by Deng in 1982. This method has been convinced as an advantageous methodology for approaching with incomplete, poor and uncertain information. To resolve the complex interrelationships among the multiple performance characteristics efficiently, the grey relational analysis can be implemented which is based on grey system theory. It also gives an effective solution to discrete data problem. With the employment of grey relational analysis, the relation between machining parameters and performance parameters can be procured[41-42].

The grey relational analysis is based on a particular concept of information. It shows situations possessing no information with black colour and those with complete data as white. The situations between these extremes are described as being grey, hazy or fuzzy. Therefore, a grey system means that a system in which part of information is known and part of information is unknown. Therefore in this analysis both the cases of no information and complete information are present. Hence it becomes difficult to come to a solution for a system with no information while a good solution exists for a system with complete information. Grey analysis does not attempt to find the best solution, but does provide techniques for determining a good solution, an appropriate solution for solving different problems.

The principal steps of GRA are firstly the performances of all alternatives are converted into a comparability sequence. This step is known as grey relational generation. A reference sequence (ideal target sequence) is developed according to these sequences. Then, calculation of the grey relational coefficient between the reference sequence and all the comparability sequence is done. Finally, the calculation of grey relational grade between every comparability sequences and the reference sequence is performed based on these grey relational coefficients. The alternative will be chosen as best choice, if the comparability sequence derived from that alternative has the highest grey relational grade between itself and the reference sequence[43-44,41-42].

The Experiments were conducted as per L9 orthogonal array, assigning various values of the levels to the process parameters. After conducting the experiment various output parameters such as material removal rate (MRR), tool wear rate (TWR) and Surface roughness have been calculated and the results are presented in the table given below.

Table 4.1 Experimental Results

Exp. No.	Current (A)	Voltage(V)	Pulse on time(us)	MRR(mm^3/min)	TWR(mm^3/min)	Surface Roughness(μm)
1	7	70	75	6.69	0.05	8.876
2	7	80	100	8.16	0.0678	7.027
3	7	90	150	11.27	0.0705	6.56
4	8	70	100	12.82	0.0369	6.89
5	8	80	150	15.27	0.0406	6.648
6	8	90	75	17.37	0.0256	8.534
7	9	70	150	16.89	0.0511	7.643
8	9	80	75	17.63	0.0364	10.376
9	9	90	100	21.23	0.0392	9.816

4.2 Optimization using Grey Relational Analysis:

Taguchi's method focuses on effective application of engineering strategies rather than advanced statistical techniques. The primary aims of Taguchi method are

- Minimising the variation of a product design to improve quality and lower the loss imparted to society.
- A proper product or process implementation strategy, which can further reduce the level of variation.

The steps involved in Taguchi's Grey Relational Analysis are:

Step 1 - In the 1st step of the grey relational analysis, pre-processing of the data was first performed for normalizing the raw data for analysis. This is shown in Table 5.2. Yij is normalized as Zij (0≤Zij≤1) by the following formula to avoid the effect of adopting different units and to reduce the variability. The normalized output parameter corresponding to the larger-the-better criterion can be expressed as

$$Z_{ij} = \frac{y_{ij} - \min(y_{ij}, i = 1,2,3,......n)}{\max(y_{ij}) - \min(y_{ij}, i = 1,2,3,....n)} \quad \textbf{(4.1)}$$

Then for the output parameters, which follow the lower-the-better criterion can be expressed as

$$Z_{ij} = \frac{\max(y_{ij}, i = 1,2,3,......n) - y_{ij}}{\max(y_{ij}) - \min(y_{ij}, i = 1,2,3,....n)} \quad \textbf{(4.2)}$$

Table 4.2 Normalized variables

Exp. No.	Current (A)	Voltage(V)	Pulse on Time(us)	Normalized values		
				MRR	TWR	SR
1	7	70	75	0	0.45657	0.393082
2	7	80	100	0.1011	0.060134	0.877621
3	7	90	150	0.314993	0	1
4	8	70	100	0.421596	0.74833	0.913522
5	8	80	150	0.590096	0.665924	0.976939
6	8	90	75	0.734525	1	0.482704
7	9	70	150	0.701513	0.432071	0.716195
8	9	80	75	0.752407	0.759465	0
9	9	90	100	1	0.697105	0.146751

Step 2- The grey relational coefficient is calculated to express the relationship between the ideal (best) and actual normalized experimental results. These are given in Table 5.3. The grey relational coefficient can be expressed as

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{0i}(k) + \zeta\Delta_{\max}} \quad \textbf{(4.3)}$$

Where $\Delta_{0i}(k)$ is the deviation sequence of the reference sequence and comparability sequence.

$$\Delta_{0i}(k) = \| y_o(k) - y_i(k) \| \quad \textbf{(4.4)}$$

$$\Delta_{\min} = \underset{\forall j \, \varepsilon \, I}{min} \; \underset{\forall k}{min} \; \| y_o(k) - y_i(k) \| \quad \textbf{(4.5)}$$

$$\Delta_{\max} = \underset{\forall j \, \varepsilon \, I}{max} \; \underset{\forall k}{max} \; \| y_o(k) - y_i(k) \| \quad \textbf{(4.6)}$$

$y_o(k)$ denotes the reference sequence and $y_j(k)$ denotes the comparability sequence. ζ is distinguishing or identified coefficient. The value of ζ is the smaller and the distinguished ability is the larger. ζ = 0.5 is generally used.

Step 3: The grey relational grade was determined by averaging the grey relational coefficient corresponding to each performance characteristic. It is given in the Table 5.4. The overall performance characteristic of the multiple response process depends on the calculated grey relational grade.

The grey relational grade can be expressed as

$$\gamma_i = \frac{1}{n} * \sum_{k=1}^{n} \xi(k) \quad \textbf{(4.7)}$$

Where, Υ_i is the grey relational grade for the i^th experiment and k is the number of performance characteristic.

Table 4.3 Individual Grey Relational Coefficient

Exp. No.	**Current (A)**	**Voltage(V)**	**Pulse on time**	**Grey Relational Coefficient**		
				Grey 1	**Grey 2**	**Grey 3**
1	7	70	75	1	0.522701	0.559859
2	7	80	100	0.831808	0.892644	0.362945
3	7	90	150	0.613502	1	0.333333
4	8	70	100	0.542537	0.400535	0.353726
5	8	80	150	0.458675	0.428844	0.338538
6	8	90	75	0.405014	0.333333	0.5088
7	9	70	150	0.416142	0.53644	0.411118
8	9	80	75	0.399231	0.396994	1
9	9	90	100	0.333333	0.417674	0.773096

Table 4.4.Grey Relational Grade

Exp. No.	**Current (A)**	**Voltage(V)**	**Pulse on time(us)**	**Overall Grey Relational Grade**	**Rank**
1	7	70	75	0.694187	2
2	7	80	100	0.695799	1
3	7	90	150	0.648945	3
4	8	70	100	0.432266	7
5	8	80	150	0.408686	9
6	8	90	75	0.415716	8
7	9	70	150	0.454567	6
8	9	80	75	0.598742	4
9	9	90	100	0.508034	5

Table 4.5: Predicted S/N ratio

I	V	T	Overall Grey	SNRA1	PSNRA1
7	70	75	0.694187	-3.17047	-2.46954
7	80	100	0.695799	-3.15033	
7	90	150	0.648945	-3.75584	
8	70	100	0.432266	-7.28497	
8	80	150	0.408686	-7.77221	
8	90	75	0.415716	-7.62407	
9	70	150	0.454567	-6.84805	
9	80	75	0.598742	-4.45521	
9	90	100	0.508034	-5.88214	

4.3 Integration of S/N ratio and Grey relational analysis

The terms Signal and Noise, are applied to the natural variation of the end product of the process with the Signal being represented by the process average and the Noise being represented by the standard deviation of that output. These ratios are commonly used within the context of design of experiments in industry to find the best parameter setting for the process input variables; i.e., the level(s) which will optimize the process output variable. The S/N ratio is a measure of the magnitude of a data set relative to the standard deviation. If the S/N is large, the magnitude of the signal is large relative to the “noise” as measured with the standard deviation. If S/N is large, then the signal is deemed to be significant – not just random variation.

From the results of S/N ratio analysis, it is found that voltage (V) at level 2, current and pulse on time at level 1 are the optimal operating conditions to perform EDM of the composite material.

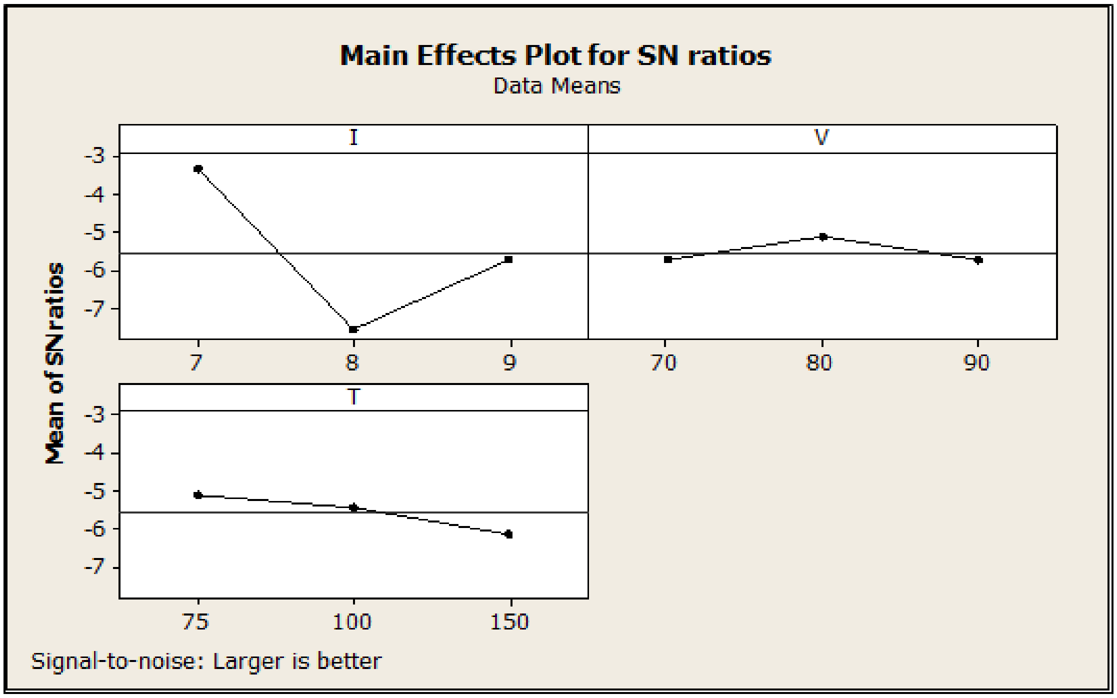


Fig 4.1: S/N Ratio graph for each parameter at different levels

Table 4.6: Response table for S/N Ratio

Level	I	V	T
1	-3.35888	-5.76783	-5.08325
2	-7.56041	-5.12591	-5.34325
3	-5.72846	-5.75402	-6.12536
Delta=max-min	4.20153	0.64192	1.04211
Rank	1	3	2

Table 4.6 shows response table for signal to noise ratio. This response table represents the effects of various input factors on Grey Relational Grade. The rank represents directly the level of effect of input based on the values of delta. Delta here represents the difference of maximum and minimum values and we calculated the value of delta for each input parameter. Here according to ranks, the effects of various input factors on Grey Relational Grade in sequence of its effect are current (I), followed by pulse on time (T_{ON}) and Voltage (V). From this analysis it can be

concluded that the most influencial parameter is current (I), followed by pulse on time (T_{ON}) and Voltage (V).

Table 4.6 shows the values of signal to noise ratio (SNRA) and Predicted signal to noise ratio (PSNRA) for grey relational grade. The value of predicted signal to noise is calculated based on the parameter setting for maximum S/N ratio. The value of predicted signal to noise is very much close to the calculated signal to noise values hence the analysis of Taguchi for signal to noise ratio is correct.

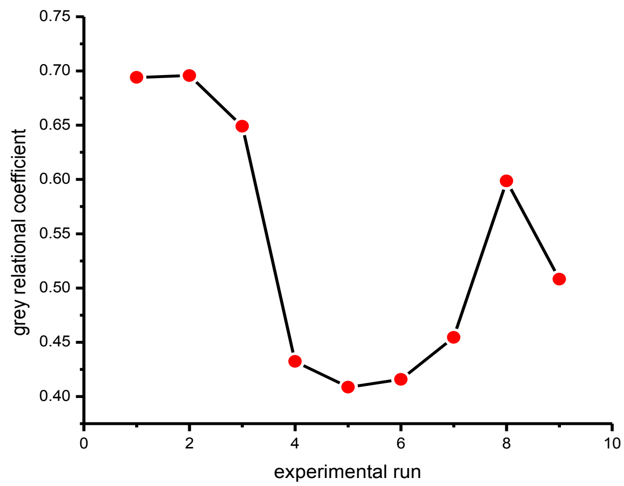


Fig 4.2: Grey Relational Grades for Maximum MRR, Minimum TWR and Minimum Ra

Step 4: Determination of the Optimal Factor and its Level Combination. From the results obtained it can be inferred that the best output is obtained at the parameter setting i.e. voltage at level 2, current at level 1 and pulse on time at level 1. The Fig. 4.2 shows the Grey relational grades for maximum MRR, minimum TWR and minimum Ra.

In the grey relational analysis, the grey relational grade is used to show the relationship among the sequences. If the two sequences are identical, then the value of grey relational grade is equal to 1. The grey relational grade also indicates the degree of influence that the comparability sequence could exert over the reference sequence. Therefore, if a particular comparability sequence is more important than the other comparability sequences to the reference, then the grey relational grade for that comparability sequence and reference sequence will be higher than other grey relational grades.

The larger the grey relational grade, the better is the multiple performance characteristics. However, the relative importance among the machining parameters for the multiple performance characteristics was predicted via S/N ratio analysis so that the optimal combinations of the machining parameter levels can be determined more accurately.

4.4 Confirmatory Results

The confirmation test for the optimal parameters with its levels was conducted to evaluate quality characteristics for EDM of copper composite material. Table 5.5 shows highest grey relational grade, indicating the initial process parameter set of A1B2C1 for the best multiple performance characteristics among the nine experiments. Table 5.8 shows the comparison of the experimental results for the optimal conditions (A1B2C1) with predicted results for optimal (A1B2C1) EDM parameters. Here A-Current, B-Voltage, C-Pulse-on time

The predicted values were obtained by

Predicted Response = Average of A1 + Average of B2 + Average of C1 – 2 x Mean of response (Yij)

The response values obtained from the experiments are MRR = 8.16 mm^3/min, TWR = 0.0678 mm^3/min and the surface roughness is 7.027 µm. The comparison again shows the good agreement between the predicted and the experimental values.

Table 4.7: Comparison of actual and predicted values

	Optimal Process parameters	
	Predicted	**Experiment**
Level	A2B1C1	A2B1C1
MRR (mm^3/min)	8.172	8.16
TWR(mm^3/min)	0.06608	0.0678
Ra(µm)	7.052	7.027

5.1 Conclusions

The larger the grey relational grade, the better is the multiple performance characteristics. After finding the grey relational grade for each experimental run S/N Ratio analysis was conducted to predict the most optimal setting. The optimal parameter combination was determined as A2 (voltage, 80 V), B1 (pulse current, 7 A) and C1 (pulse on time, 75 µs).

Taguchi's Signal – to – Noise ratio and Grey Relational Analysis were applied in this work to improve the multi-response characteristics such as MRR (Material Removal Rate), TWR (Tool Wear Rate) and Surface Roughness of Cu-Al_2O_3 metal matrix composite during Electric discharge machining process. The conclusions of this work are summarized as follows:

1. The optimal parameters combination was determined as A2B1C1 i.e. pulse voltage at 80 V, pulse current at 7A, pulse ON time at 75µs.

2. The predicted results were checked with experimental results and a good agreement was found.

3. This work demonstrates the method of using Taguchi methods for optimizing the EDM parameters for multiple response characteristics.

5.2 Future Scope:

Above mentioned work can be extended in further directions:

- For experimental analysis different material properties such as % Al_2O_3 and mesh size of powders can also be considered.
- Apart from EDM, ECM may be carried out in order to investigate the machinability of these composites.
- Mathematical model may be derived in terms of process parameters to optimize the process parameters in EDM of MMCs.

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