EXPERIMENTAL INVESTIGATION TO EVALUATE THE MACHINING CHARACTERISTICS OF METAL MATRIX COMPOSITE BY ELECTROCHEMICAL DISCHARGE MACHINING

DISSERTATION II

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

MASTER OF TECHNOLOGY
IN
MANUFACTURING ENGINEERING
By
Anmol Morgan
(Reg. No. 11203128)

Under the Guidance Of

Ranjit Singh
(Assistant Professor)

LOVELY PROFESSIONAL UNIVERSITY
LOVELY PROFESSIONAL UNIVERSITY
PHAGWARA (DISTT. KAPURTHALA), PUNJAB

(School of Mechanical Engineering)

Lovely professional university

Phagwara, Kapurthala, Punjab, India, 144411

JUNE 2017

CERTIFICATE

I, **Anmol Morgan**, hereby certify that the work which is being presented in the dissertation entitled **"Experimental investigation to evaluate the machining characteristics of metal matrix composite by electrochemical discharge machining"** in partial fulfillment of the requirement for the award of degree of **Master of Technology in Manufacturing Engineering** and submitted in Department of Mechanical Engineering, Lovely Professional University, Punjab is an authentic record of my own work carried out during period of Dissertation under the supervision of **Mr. Ranjit Singh**, **Assistant Professor**, Department of Mechanical Engineering, Lovely Professional University, Punjab. The matter presented in this dissertation has not been submitted by me anywhere for the award of any other degree or to any other institute.

Date: (**Anmol Morgan) Reg no. 11203128**

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

Date: **(Ranjit Singh) UID : 16990**

COD (ME)

____

The external viva-voce examination of the student was held on successfully _______________

Signature of Examiner

LOVELY PROFESSIONAL UNIVERSITY PUNJAB (INDIA)

CANDIDATE'S DECLARATION

I, Anmol Morgan, Reg. No. 11203128 hereby declare that the work presented entitled **"Experimental investigation to evaluate the machining characteristics of metal matrix composite by electrochemical discharge machining"** in partial fulfillment of requirements for the award of Degree of Master of Technology (Manufacturing Engineering) submitted to the Department of Mechanical Engineering at Lovely Professional University, Phagwara is an authentic record of my own work carried out during the period from JAN 2017 to JUNE 2017, under the supervision of Mr. Ranjit Singh (Assistant Professor), Department of Mechanical Engineering. The matter presented in this thesis has not been submitted in any other University/ Institute for the award of Degree of Master of Technology. Furthermore, I also declare that I will not publish this work in any other Journals/ Conferences/ Workshop seminars except the one chosen by supervisor. The presented work is the property of Lovely Professional University, Phagwara. If I found violating any of the above conditions, University has right to cancel my degree.

Date: Signature of Student

ACKNOWLEDGEMENT

Nothing can be achieved without an optimal combination of inspiration and perspiration. The real spirit of achieving a goal is through the way of excellence and discipline. I would have never succeeded in completing my task without the cooperation, encouragement and help provided to me by various personalities.

I owe my special thanks to Mr. Ranjit Singh, Assistant Professor, Department of Mechanical Engineering, Lovely Professional University, Phagwara, who helped and guided me for this work. His encouraging remarks from time to time greatly helped me in improving my skills.

I am also thankful to Mr. Jaswinder Singh, COD, Department of Industrial Engineering, Lovely Professional University Phagwara, I wish to place on record my gratitude for all those who have been instrument in bringing my work to this stage.

I do not find enough words with which I can express my feeling of thanks to all my family members and friends for their help, inspiration and moral support which went a long way in completion of my thesis.

Above all I render my gratitude to the ALMIGHTY and MY PARENTS who bestowed me self-confidence, ability and strength to complete this work.

Anmol Morgan
Reg. No. 11203128

ABSTRACT

In aerospace and aeronautics metal matrix composites are used frequently because of the high strength to weight ratio. But the machining of metal matrix composites for complex shape is very tedious as well as expensive because these composites are hardened using a ceramic due to which the machining is possible using polycrystalline diamond and cubic boron nitride tools. Therefore, a hybrid process like electrochemical discharge machining is more efficient. The Optimization of the process parameters such as voltage, current and concentration of electrolyte by using Taguchi method was reported while machining of particulate reinforced aluminum matrix composite (AL 2014/ B_4C) on basis of MMR and surface roughness. Sodium chloride is used as electrolyte while the tool electrode and auxiliary electrode as copper and steel are used respectively. The optimised machining parameters for more MRR are of voltage (80), electrolyte concentration (20), and current (8) where Voltage was found to be the most significant factor affecting MRR. The optimised cutting parameters for good surface finish are voltage (60), electrolyte concentration (17.5), and current (7) where Current was found to be the most significant factor good surface finish. With increase in voltage, electrolyte concentration and current the material removal rate increases

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

In aerospace and aeronautics metal matrix composites are used frequently because of the high strength to weight ratio. But the machining of metal matrix composites for complex shape is very tedious as well as expensive because these composites are hardened using a ceramic due to which the machining is possible using polycrystalline diamond and cubic boron nitride tools. therefore, non-traditional machining is more efficient. Non-conventional machining methods like laser jet machining and water jet machine can allow machine MMC's with high material removal rate but it is causes surface and subsurface flaws. More over the 3-D shaping with help of both of these methods is difficult from non-traditional machining techniques. But processes like electrical discharge machining and electrochemical machining. But a hybrid process like Electrochemical discharge machining is five to fifty times more efficient in machining than both ECM and EDM. But there are a lot of problems in which the work is needed to be done like low material removal rate the high risk of tool breakage, and the presence of various types of defects on the machined surface. As to ECM, surface quality and processing efficiency are two important issues that need to be addressed. Turning to the hybrid process of electrochemical discharge machining (ECDM), which has been shown as a promising method for machining MMCs, however, the problem of poor surface finish still cannot be easily overcome. Recognizing these problems, it is apparent that the ECDM process must be further improved in order to meet the challenges faced when shaping advanced composite materials. Another problem in WEDM-LS of Al-based composites was that abnormal arcing was repeatedly observed. As a result, low MRR, poor surface finish, and severe subsurface damage occurred. These problems arise mainly due to the fact that ceramic reinforcement phases normally act as electrical insulators, and many of their physical properties, such as the melting and vaporization points, are usually a few times higher than those of the matrix material. It is envisaged that under a combined action of spark erosion and electrochemical etching, the reinforcement phase will be removed more readily and a much higher machining efficiency, and a better surface finish can be obtained. It is difficult to machine some materials like ceramics and composites, specially composites which have very complex contour. Now these days a newly advanced material is made that is metal matrix composites which have high resistance to wear and corrosion, high strength and low thermal coefficient of expansion. Because of high hardness and reinforced material, it is difficult to machine using traditional methods. Therefore, to deal with this a hybrid process combining electrochemical machining and electrical discharge machining used for machining. The process formed is electrochemical discharge machining which help to machine both conductive as well as nonconductive materials with more material removal rate, better surface finish, and easy to machine materials with difficult contour. This process involves electrochemical action and electric discharge to remove material. The material removal rate depends on various parameters such as feed rate, applied voltage and current, work piece material, gap between Electrode and work piece, concentration of electrolyte.

It is envisaged that under a combined action of spark erosion and electrochemical etching, the reinforcement phase will be removed more readily and a much higher machining efficiency, and a better surface finish can be obtained.

1.1 MACHINING

Machining is the removal of the unwanted material from the workpiece to obtain the desired shape size and surface quality of the product. Usably all the casting products needs machining to achieve the desired precision and tolerances. In stone age removal of the material was achieve using simple hand tools like bone, sticks, stone. Than these stone age tools were bronze and iron tools. These tools were driven by using the power of water steam and later of electricity for metal cutting. These power driven meta cutting machine are known as traditional machining process. But with the need of better surface finish, less tolerance and for the machining of complex contour of hard materials which cannot be machined economically with traditional machining than Non-traditional technique was introduced. Machining is usually knowing as the final finishing process for a work-piece produced by the casting and forming process before they are transported for assembly and use. Now a days micro machining is an important issue for machining 3D shape and structures with the tolerance level of micrometer. More over in Nano machining removal of atoms or molecules is done to produce parts of microelectronic, automobile and air-craft manufacturing industries.

The developments of metal cutting machine stared with the invention of cylinder that was changed to a roller guided by the journal for transporting stone from one site to another site. The invention of the rollers started the introduction of first wooden drilling machine in 4000 pieces. This machine uses shape stone which act as a tool. The turning machine was introduced in 1840 after the invention of deep hole boring machine by Leonardo da Vinci (1452-1591). Than slide ways for tailstock and automatic tool feeding were added in previous design. In 1824 – 1905 plainer and shapers were introduced and modified by sellers. First milling machine was built by Whitney. The first cylindrical grinding machine was introduced by brown and sharp in 1874. Than these traditional machines were modified with the introduction of copying technique, cams and automatic mechanism to reduce labor and to increase the product accuracy. The product accuracy and uniformity was enhanced with the introduction of numerical control technology. In 1953 computer numerical control and direct numerical control was introduced. In modern era of machining harder, stronger and tougher material which are difficult to machine are also used. Hence nontraditional came into practices to machine hard material with better surface finish and more economically. It is easily to make complex shape using these methods hydrides machines were introduced using two or more nontraditional processes for better machining.

1.1.1 CLASSIFICATION OF MACHINING PROCESSES

Material removal process is broadly classified as followed

1. Traditional machining
2. Non-traditional machining

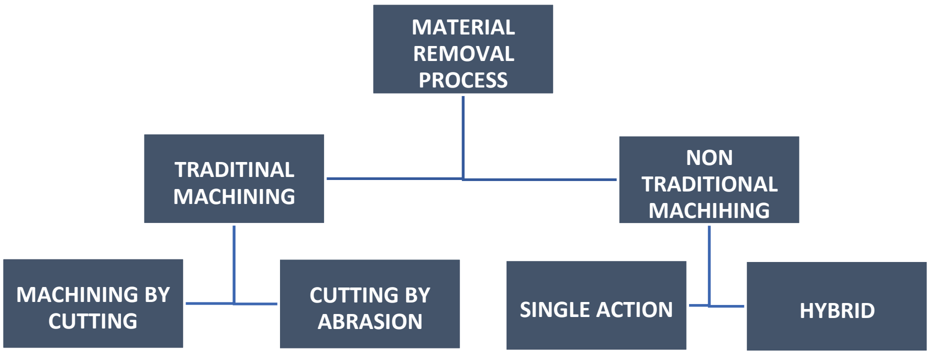


Figure 1: Classification of Machining Process

1.1.1.1 TRADITIONAL MACHINING

Traditional process is also known as conventional machining. In traditional machining, the material is remove from the workpiece with the help of the tool which is harder than the workpiece material. The tool must penetrate the workpiece for machining. For forming a desired shape, a specific relative motion between the tool and the work-piece is responsible. The process is considered to be non-traditional process if the work-piece and tool are not in contact or there is no relative motion between them. It is further classified on the basics of machining action.

1. Machining by cutting
2. Machining by abrasion

Machining by cutting

During machining by cutting the workpiece material is penetrated by tool to a certain depth and there is a relative motion between workpiece and tool. In this turning process manufacture cylindrically parts, shaping and milling produces the flat surfaces, whereas drilling process producing holes.

Machining by abrasion

In abrasion machining process, the material is removed by the hard, angular abrasive particles or grits which may and or may not be bounded to form a tool. In abrasive machining, all the abrasive particles with their cutting edges randomly oriented. Also, undeformed chip thickness is small.

1.1.1.2 NON TRADITIOANL MACHINING

In non-traditional machining processes, the material is removed by the mechanical, thermal, chemical and electrochemical action. The process is considered to be non-traditional process if the work-piece and tool are not in contact or there is no relative motion between them. It is further classified on the basics of machining action. Material remove occur with and without chip formation. The tool may or may not be harder than that of the workpiece material. The machining or ceramics and composite is very difficult because they are hard therefore non-traditional machining process are used to machine these materials. Non-traditional machining processes are classified on the basis on number of machining action which causes the removal of material.

1. Single action non-traditional machining process
2. Hybrid machining

Single action non-traditional machining

When material removal is caused only one machining action. These are further classified based on source of energy generate that machining action.

1. Mechanical machining
2. Thermal machining
3. Chemical and electro chemical machining

Mechanical machining

The material is removed due to the mechanical movement of the abrasive particles. In ultrasonic machining, the abrasive particle starts vibrating which causes erosion of the woke-piece and in abrasive jet machining the stream of abrasive particle impinge on the workpiece surface with high pressure which causes the material erosion

Thermal machining

The removal of material is carried by melting or vaporization of work-piece material. In EDM electro chemical discharge machining the removal of the material is caused by the electrical discharge generated between the tool and workpiece by the nonconducting fluid (dielectric fluid). In EDM the material is removed with the help of high velocity focused stream of electron. In laser beam machining the light energy from a laser is used to remove material.

Chemical and electrochemical machining

The machining of the material is carried out through the ion in an etchant in photochemical machining. In electrochemical machining, the removal of material is due to the ion transfer in an electrolytic cell.

Hybrid machining

The combination of two or more machining action are used for material removal process. It is made to use of combine advantage of both processes. Example electrochemical discharge machining is the combination of ECDM and EDM in which chemical and thermal action are used for material removal.

1.2 ADVANTAGES OF NON TARDITIONAL MACHINING

High accuracy and surface finish: Parts machined by non-traditional machining processes has better surface finish as compare to traditional machining processes as there is no or very less tool and work-piece contact therefore having less friction tool and workpiece. Micro machining is possible with non-traditional machining process because of its high accuracy.

Tool life: As there is no or very less contact between the tool and the workpiece therefore wearing of the tool is very less. Therefore, more tool life is possible in non-traditional process.

Machining of hard material: It is difficult to machine hard material with traditional machining processes because the machining hard material like composite and ceramic is only possible by poly crystalline diamond and cubic boron nitride tools which are very expensive therefore non-traditional machining processes are more efficient. More efficient and more economical. Thin and fragile materials can be machined without distortion.

1.3 ELECTRO CHEMICAL DISCHARGE MACHINING

It is a hybrid non-traditional machining process which uses thermal and chemical action for material removal. It combines feature of both electrochemical machining and electrical discharge machining. The material is removed is carried out by the vaporization of the work-piece material because of spark generated between the tool and workpiece. Material is also removed due to the erosion of the material of the because of chemical action of electrolyte. It a discharged based material removal processed which can be used for micromachining. This method can also be used for machining non-conducting material. It can be machining micro channel, 3D microstructure and micro holes of non-conducting material. In this ECDM process the work piece is submerged in electrolyte such as NaNO3, NaOH and KOH and pulsed voltage is applied. The tool Electrode acts as cathode and contour Electrode as anode. A low voltage is applied to the initiate the electrolysis which causes the bubble formation. When we increase the current density the rate of bubble formation also increases and the diameter of bubble also increases. Then if you further increase the voltage at some voltage bubble coalesce causing the gas film formation at anode. This voltage is called critical applied voltage. At this critical voltage, high potential difference is created between tool and workpiece. Then this potential difference increases cause the arc is generated tool Electrode and electrolyte. Then due to thermal erosion and vaporization machining is achieved. Machining is also due to chemical etching.

1.3.1 HISTORY OF ECDM

Kura Fuji and Suda of Japan in 1968 first introduced electrical discharge drilling, which was hybrid process and was the combination of EDM and ECM. They described that it is possible to drilling micro-holes in glass. In the year 1973, Cook proposed a new name for this process that is discharge machining said that the process introduced by Kura Fuji and Suda is different from EDM and ECM. They performed machining of non-conductive materials using this process and studied the effect of the electrolyte. In 1085 Tsuchiya et al named this process as wire electrolyte discharge machining and proved that this method can be used for the machining of non-conducting material like glass and ceramic. In 1997 Bask and gosh descried that the material is removed with both melting as well as chemical reaction in ECDM. They prepared a modal to find the material removal rate or varying parameters. In year 2004 Skrabalak et al made a modal to evaluate the current of electrochemical dissolution and electro discharge machining. In 2004 Mediliyegebara et al prepare a control strategy for ECDM by studying the pulse classification system.

In 2005 Wuthrich and Fascio give a review on ECDM methods when 40 year of its first mention in literature. The work emphasized the electrochemical aspects and indicated its limitation and their potential solution. In 2006 Yang et al descried that when silicon carbide abrasive particles are adding to electrolyte in wire electrolyte discharge machining, the surface finish was improved and decrease in discharge energy. In 2009 Cao et al descried the machining of 3D micro structure of glass they reported that with the use of load cell and less immersion depth of electrode required voltage is reduce. Therefore, high aspect ratio structure with more precision can be machined. Yang et al reported that tool with spherical whose diameter then its cylindrical body can be performed deep drilling operation in ECDM. The observed that the area of contact between tool and work piece reduces due to curved surface of the tool. In 2013, Liu et al elaborated a grinding aided electrochemical discharge machining process for the of particulate bolstered metal matrix composites. In this process material is removed by mechanical grinding, discharge erosion and electrochemical dissolution. In 2014, empirical methods were used for the investigation of discharge energy which causing large perdition error of material removal rate. So, to overcome this jiang proposed an experiment based stochastic modal for the estimation of the spark energy. Abishek B. Kamaraj et al, (2015) studied the mathematical model to predict overcut during electrochemical discharge machining. The model captures the result of machining time and solution concentration on overcut. The concentration of the solution will affect on the overcut. Only variation within 15 % can evaluate by the model. The effect of the tool diameter on the overcut is very less or it is in the microns. Reducing the solution concentration to 1 M, a through micro hole with a side magnitude relation of 12 has been join on a one.2-mm-thick boro glass plate using carbide tools. In this model, also evaluation of the thermal effects on the material removal rate at high temperature, examine the high aspect ratio of the marching. Zhaoyang Zhang et al, (2016) study to explore study to explore the properties of electrochemical discharge effect based on pulse power supply. The nonconductive and hard brittle materials like glass and ceramics are very difficult to machining on the EDM but by the spark assisted chemical engraving it is very easily machined. In this study found the critical voltage of the electrochemical discharge. Also, define the concentration of the solution, rotational velocity, dimeter, pulse frequency etc. while changing of the parameter except rotational velocity, has great effect on the critical voltage. The mean electric current and film formation time were also explained in electric current signal. The study carried out initial voltage is best for the machining accuracy.

1.3.2 MECHANISM OF MACHINING

Mechanism of machining is carried out in two main stages that is gas film formation and stability of gas film. In ECDM process the gas film formation is carried out first in which due to the bubble coalesce formed on the surface of Electrode cause local evaporation of electrolyte take place due to Boyle heating. High electrical charge causes growth in diameter of bubble and density of bubble. It consists of three zones.

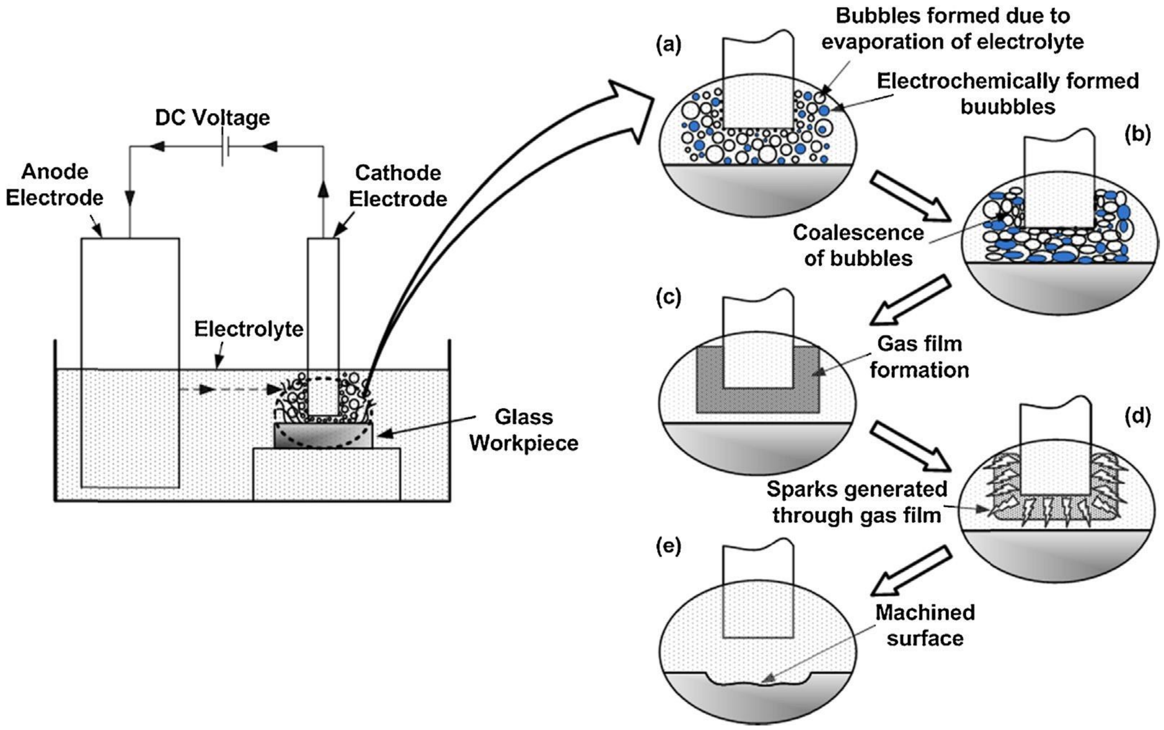


Figure 1.2 Schematic Diagram Formation of Gas Film And Associated Machining; (A) Electrolyte Evaporation (B) Coalescence Of Bubbles, (C) Gas Film Formation, (D) Discharging/Sparking Through Gas Film, And (E) Thermally Eroded

1. Adherence zone-it is the initial zone in which bubble is in direct contact with Electrode surface and they grow in number. The bubble which is in direct contact they coalesced in zone.
2. Diffusion zone- it is zone when a bubble reaches it departure stare come together in very large number causing bubble diffuse in diffusion region
3. Bulk region- it is the last stage in which there is no further growth of bubble because the gas reaches the super saturation. Super saturation region near to bulk solution causes no further bubble growth.

In this process gas film act as a dielectric medium for discharge and the major part of the machining is done by this discharge which is mainly dominated by gas film quality. Gas film formation depends upon serval factors like surface tension, temperature gradient between tool and electrolyte, current density, electrolyte tool emersion depth, tool shape and electrostatic force between bubble and electrode. The gas film formation is carried by coalescence of hydrogen bubble formed by the electrochemical reaction. Due to the electrochemical reaction, at cathode and at anode oxygen gas is generated.

$2H_2O + 2e^- \rightarrow 2(OH)^- + H_2$ at cathode

$4(OH)^- \rightarrow 2H_2O + O_2 + 4e^-$ at anode

The rate of the bubble formation depends upon current density. The resultant of the surface tension and buoyancy forces cause bubble attachment then theses bubble move in upward direction whereas surface tension resist this movement. When the applied voltage is equal to critical voltage coalescence of bubble start which causes gas film formation. It is important for the gas film produce to be stable to avoid rough surface and surface falls. The stability of the gas film is controlled by supplied pules voltage. The gas film thickness should less for better surface finish. When gas film thickness is reduced the critical voltage also decrease. Gas film thickness can be control by

1. Using hydrodynamic fluxes: it can be produced by using a rotating tool or reciprocating workpiece.
2. Wettability of electrode: By increases the wettability the gas film thickness can be stable.
3. Pulse voltage:
4. Electrolyte concentration: With increase in the electrolyte concentration with increase in concentration the rate of electrolysis. Therefore, more number of $(OH)^-$ ions causes decrease in surface tension. This leads to thinner gas film and more accuracy

After completion of their stages there is formation of gas film surrounded the tool Electrode due to bubble diffusion, when the voltage beyond the critical applied voltage. The characteristic of gas film is based on electrolyte, temperature. Higher the electrolyte bulk temperature more will be gas film uniformity. A small spot on the active Electrode act as starting point of discharge and propagates in gas film electrolyte interface. This cause less conductivity of electrolyte. due to this material removal take palace by evaporation, chemical etching and melting.

1.3.3 FACTOR AFFECTING THE MATERIAL REMOVAL RATE

Material removal rate, surface quality and tolerance of the machined part defines the performance of the machining process. The performance of ECDM depends upon various factors as follows.

1. Chemical etching: The optimization of electrolyte supply to the machining zone enhances chemical etching. While deep drilling operation continues supply of

electrolyte to the electrode tip is important. This can be achieved by electrode motion.

2. Tool electrode shape: tool electrode with small cross section area has higher charge density therefore causing high material removal rate. Needle tool electrode concentrate the discharge. Therefore, there is high material removal rate. But at the cost of poor surface finish therefore, spherical tools with less cylindrical diameter are used for better surface finish.
3. Tool electrode rotation: By rotating the tool electrode surface finish accuracy and material removal rate increases. Machining is more efficient at slow rotation but more than 25 rpm in stable gas film formation is start.
4. Effect of voltage: Due To increase in voltage there is increase in material removal rate. But after reaching certain point the effect of increasing voltage is reversed means MMR IS decreased, also high voltage causes micro cracks in surface of work piece. Doloi BN et al proposed that in ceramics when we increase the voltage above 100V the work piece is totally damaged.
5. Feed rate- optimum feed rate should be set for proper machining. While increasing it surface quality is poor and decreasing it will leads to formation of heat affected zone.
6. Wettability- It affects the surface roughness and porosity. It effects upon stability of gas film. In case of deep drilling there is difficulty in wettability because of machine material in present in hole.
7. Electrolyte head- we have to maintain the electrolyte head above the work piece for arc
8. Effect of depth of hole- there is limiting depth after which machining is not possible or not proper because there is potential drop at a certain point above which increment in voltage does not affect the penetration of the hole.
9. Machining gap- it the gap between work piece and tool is known as machine gap. it affects the thickness and stability of gas film. Maintaining the machining gap in drilling is difficult.
10. Concentration of electrolyte- MMR directly proportional to the concentration because of higher concentration there are more ions that is cation and anion and large number of spark will have developed. There is also a peak point after which

further increase in concentration causes decrease in MMR because it becomes more viscous. But the surface finish of the workpiece is improved.

11. Abrasive mixed electrolyte- MMR increases when we mix abrasive particles in electrolyte. But it needs rotation or vibration because it damages the gas film.
12. Inter electrode gap- it is inversely proportional to material removal rate. As we increase this gap resistance is increased. It is used to control the material removal rate.
13. Temperature of electrolyte- It is directly proportional to material removal rate because there is increase in electrical conductivity therefore increase the spark rate. The chemical etching is improved due to increase in the ion mobility therefore causing better surface finish.
14. Reinforcements in MMCs- With increase in contents of reinforcement in metal matrix composite it is difficult to machine it.

1.4 SURFACE TOPOGRAPHY

It is difficult to display ideal geometrical surface of machined surface. Both macro and micro irregularities are there on the machined surface. The difference forms the nominal surface of the third up to sixth order is known as surface roughness. The order of deviation is set by the international stranded. The first and second order of deviation includes flatness, circularities and waviness. Reason for the first and second order of the deviation are abnormality in the shape of the workpiece, flaws in the machine tool. Failure of tool holding device, machine vibrations and nature of the workpiece material. Crakes disintegration and periodic trenches come under the categories of third and fourth order the main reason of third and fourth order deviation is tool geometry, cutting tool edges, type of the chip flow during machining and other primary machining parameter such as depth of cut, cutting speed and feed rate. Fifth and sixth order of deviation comes due to change in structure of workpiece material. In this deviation, there is change in the physical and chemical changes in the grain and lattice scale like slip, diffusion, oxidation, residual stress etc. The various order or deviation

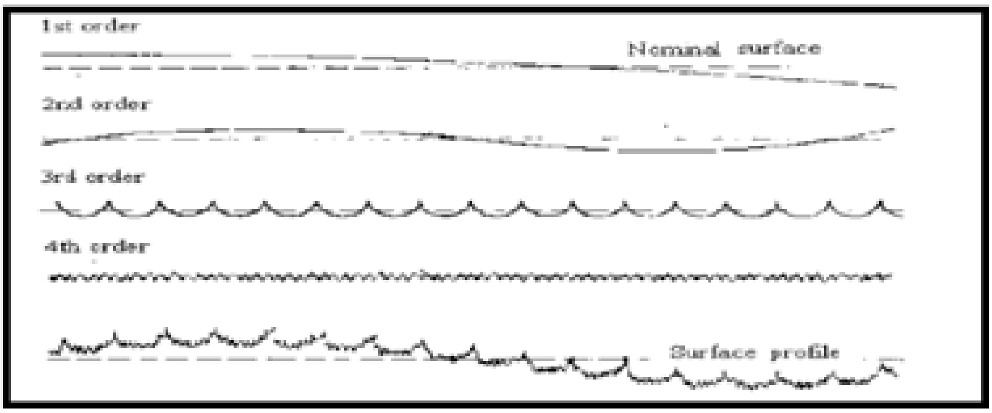


Figure 1.3: Surface topography

Ref:Mc Keown, Precision Engineering, Tata McGraw-hill (2001)

CHAPTER 2

LITERATURE REVIEWS

1. Sumit K. Jui, Abishek B. Kamaraj, Murali M. Sundaram (2013) studied the High aspect ratio of micromachining of glass by electro chemical discharge machining (ECDM). Tungsten carbide microelectrodes manufactured using PECMM were used as micro tools for the high aspect ratio micro ECDM of glass. It was determined that rotation of the tool electrode improves the circularity of the machined hole, at same time not affecting the ECDM parameters like the critical voltage and the critical current. NaOH is used as electrolyte to machine glass. using a lower concentration electrolyte of 1 M reduces the overcut of the machined holes improving its aspect ratio. An aspect ratio of 11 was achieved on glass with 1 M NaOH and a 30-micrometer tungsten carbide tool fed at .0001 mm/s using 40 V. at higher electrolyte concentration the overcut increases. Due to decrease in the tool wear and overcut the value of surface roughness varies from 250 to 350 nm. By decrease the electrolyte concentration the tool wear reduces and heat transmitted to the workpiece decreases. With higher electrolyte concentration, more material is machined from the top surface of the workpiece material. Therefore, causing more hole tapper.
2. Zhaoyang Zhang et al, (2016) study to explore study to explore the properties of electrochemical discharge effect based on pulse power supply. The nonconductive and hard brittle materials like glass and ceramics are very difficult to machining on the EDM but by the spark assisted chemical engraving it is very easily machined. In this study found the critical voltage of the electrochemical discharge. Also, define the concentration of the solution, rotational velocity, dimeter, pulse frequency etc. while changing of the parameter except rotational velocity, has great effect on the critical voltage. Three electrolytes $NaNO_3$, KOH and NaOH were evaluated on pulsed ECDM setup. While machining of soda lime glass tungsten carbide was made tool (cathode) and graphite as anode. NaOH and KOH has lesser critical voltage than $NaNO_3$. The mean electric current and film formation time were also explained in electric current signal. The study carried out initial voltage is best for the machining accuracy. The critical voltage decreases with increase in electrolyte concentration. Applied voltage is reduced at higher electrolyte concentration. The critical voltage increases when there is

increase in diameter of the tool. By raising pulse frequency, the critical voltage is also increased.

3. Cheng-Kuang Yang et al, (2011) studied the enhancement of ECDM efficiency and accuracy by spherical tool electrode. It is non-traditional processing technique. In which high accelerated chemical etching and high temperature melting use under the high electrical energy discharging. Machining cannot be larger than 250 microns. Workpiece material is quartz tungsten carbide is used as tool and KOH and OH^- was used as electrolyte and graphite is employed as an anode. The machining of small though holes with better accuracy was achieved by using spherical electrode tools. Curved surface on the spherical tool electrode decrease the area of contact between the work piece and electrode cause easily flow of electrolyte to the electrode end and increasing the rate of gas film and there is high performance micro -hole drilling. Comparison between machining depth of 550 millimeters achieved by standard cylindrical tool conductor additionally the} planned spherical tool conductor shows that machining time was reduced by 83% whereas hole diameter was also small by 65%. There is comparison between the flat electrode and spherical electrode and it is found spherical electrode far better. And both machining depth and machining time improved.
4. JW Liu, TM Yue , et al (2010) studied discharge mechanism of particulate reinforced metal matrix composites (MMC) in electrochemical discharge machining. This experiment predicted the maximum field strength position on the bubble surface and critical breakdown voltage to initiate discharge. The metal matrix composite of aluminum with Al 359 alloy with 20 % of volume of SiC particulates was machined. The electrolyte used is NaNo3. Steel tool is employed for machining. The parameters studied influence current, duty cycle, pulse duration and electrolyte concentration on ECDM waveforms. The rise in duty cycle, current, pulse duration or electrolyte concentration advances discharge energy in ECDM. The tool wear of ECDM was compare with the ECM, it was reported there is less eroded crater wear in ECDM as compare to EDM. The field strength was maximum at an angle of 901 when held perpendicular to the vertical line (L) between the two electrodes. The test results also shown that voltage waveform includes charging phase, then breakdown followed by a period of discharge in ECDM, with the discharge maintaining voltage similar to that of an EDM discharge.

5. Palani Sivaprakasam, P. Hariharan, et al (2013) studied the Optimization of Micro WEDM Process of Aluminum Matrix Composite (A413-B4C): A Response Surface Approach. The influence of different parameters like voltage, capacitance, and feed rate on the material removal rate (MRR), kerf width (KW), and surface roughness (SR) was examined. Aluminum alloy (A413) -(9% B4C) metal matrix composite is used as a work piece material on which he machining is to be done. Zinc coated copper wire used as tool for machining. RSM with central composite design (CCD) was used. For the optimization of process parameters second order mathematic modeling and ANOVA was used. The second order mathematical modeling was presented for predicting optimal conditions of MRR, KW, and SR. Predicted and measured values were reasonably close so that the models could be effectively used for predicting the machining performance of the micro-WEDM process. The material removal rate is increases with increase in voltage due to the increase in discharge energy.
6. Sanjay K. Chaka, P. Venkateshwara Rao (2007) studied the Trepanning of Al2O3 by using abrasive electrode in electro-chemical discharge machining (ECDM) process with pulsed DC supply. Thermal shocks at high voltage resulted in the formation of micro cracks with increased depth of tool. The material to be machined is Al2O3. The electrolyte used is NaOH and KOH. A diamond embed abrasive rode was employed as cathode and rotation of 24 rpm was given to the cathode and graphite is used as the anode. By using pulse DC, we can minimize the tendency of crack formation at high voltage. As compared to conventional copper electrode abrasive electrode can drill deeper holes with better efficiency due to additional electrical discharge and cutting action during ECDM process. At higher voltage cracks are produced at the machined surface. To overcome this pulse DC is used. Better dimensional accuracy was achieved due to the insulative nature of the abrasive particles. Better surface finish was achieved due to pulse DC supply.
7. Min-Seop Han, Byung-Kwon Min, Sang Jo Lee (2011) studied the Microelectrochemical discharge cutting of glass using a surface-textured tool. WECDM process shows low surface integrity by using travelling wire when compared with micro-ECDM which works on high working voltage and long reactive tool length. A surface texture tool was fabricated using EDM then the tool was made less reactive by using ceramic tubes and nickel plate was inclined. The material used is soda lime glass of 4 mm thickness and30% of wt NaOH as electrolyte is used . In case of smooth tool,

the machining was not possible less than 38 VDC but the minimum voltage was 10 VDC for 2D contoured tool. It was found that to increases the average thickness of the gas film we should have the longer reactive tool length and therefore increasing the material removal rate. A surface texture tool was fabricated using EDM then the tool was made less reactive by using ceramic tubes. 0.3 micrometer Ra was machined.

8. Nilesh Ganpatrao Patil & P. K. Brahmankar (2010) studied the determination of material removal rate of metal matrix composites in wire electro-discharge machining which used dimensional analysis. In WEDM the material removal depends upon the physical properties of the workpiece material, semi-empirical model was made and machining parameters chosen were pulse on time and average gap voltage. The Aluminum with silicon carbide particulate metal matrix composite is machined in this experiment. For the development of the model the dimensional analysis quasi-Newton and nonlinear estimation technique simplex technique were used. The results show that with increasing the percentage of reinforcement in the metal matrix composites results in decreased material removal rate. The reduction in MRR is almost 12% with an addition of 10% in ceramic reinforcements. Models such as RSM and the semiempirical model show more than 99% predictability. The Buckingham's π theorem and Π-theorem is used for dimensional analysis.
9. JW Liu, TM Yue, et al (2009) has studied the Wire Electrochemical Discharge Machining of Al2O3 Particle Reinforced Aluminum Alloy 6061. . The evaluation of machining voltage, current, pulse duration, and electrolyte concentration, on material removal rate (MRR) is done. The work piece used in this study is metal matrix composites MMCs. It consists of aluminium 6061 with reinforced in 10 vol% Al_2O_3 (10ALO) or 20 vol% Al_2O_3 (20ALO). A high voltage or a long pulse duration minimize the material removal rate in both 10% and 20% Al_2O_3 particulates reinforced metal matrix composite. The electrolyte used is, $NaNO_3$ with concentration range between 0.25 wt% and 1 wt% and molybdenum wire is employed as the tool electrode. Material removal rate is inversely proportional to the percentage of Al2O3 particulates in metal matrix composites. A machining current is directly proportional to the MRR. When the results were simulated it was found that when an electrolyte is used in place of of deionized water, high current densities were around the ceramic particulates. At higher applied voltage, the material removal reduces due to the presence of debris present at the machining gap.

10. D. Satishkumar et al (2011) studied the Investigation of wire electrical discharge machining characteristics of Al6063/SiCp composites. Aluminum alloy (Al6063) and silicon carbide (SiCp) a metal matrix composite is machined. SiC particulates are used to reinforce Al6063 with 5%, 10% and 15% volume fractions. Bass wire was employed as tool electrode. The analysis of variance and response graphs used to analyze the results. Comparison of results of metal matrix composite (Al6063\SiCp) with results of unreinforced Al6063 was done. Influence of process parameters on the surface textures is very less in case of wire eroded aluminum matrix composite due to the occurrence of recast/ re-solidified layer of aluminum. It was verified that the material removal rate is inversely proportional to the % volume fraction of SiC particulates in the aluminum matrix composite. On the other hand, the surface roughness Ra is directly proportional to the % volume fraction of SiC particulates in the MMCs.
11. .Mudimallana Goud, Apurbba Kumar ,et al (2016) presented a review on Material Removal Mechanism and Possibilities to increase the Material Removal Rate (MMR) in ECDM. The article explains mechanism of material removal in ECDM and found some of future approaches. The future efforts to increase material removal rate in ECDM were discussed as well by combining abrasive particles mixed electrolyte with appropriate tool electrode motion for better performance of the process. The proper gap between the electrode and electrolyte helps in improving the material removal rate. It was found that current and material removal rate are directly proportional to each other.
12. Zhang Yan et al (2016) studied the Machining of a film-cooling hole in a single-crystal super-alloy by high-speed electrochemical discharge drilling. Aero engine turbine blades are manufacture using single crystal super-alloy. These materials are very hard in nature. Therefore, it is very tough to machine. The aero engine industry demands high accuracy and better quality. Nickel based single crystal super alloy is machined using tube electrode high speed electrode discharge drilling. For the optimization of the process parameter Taguchi method was employed. Than results of TSECDD was compared with the electrical discharge drilling. After comparison recast layer was eliminated in TSECDD due to the electrochemical dissolution. With increase in pulse duration the tapper angle is also increases. MMR is directly proportion to the pulse duration.
13. Zhang Yan et al (2015) studied the effect of low-conductivity salt solution in tube electrode high-speed electrochemical discharge drilling. For the machining of the film

cooling holes tube electrode high speed electrochemical discharge drilling is used because it is a tedious task to machine super-alloy as there very hard in nature. By using a low conductivity salt solution better surface finish and high machining rate was achieved. Salt solution with different conductivity was used for the investigation. With increase in conductivity of the salt solution the material removal rate is decreases. The salt solution conductivity is directly proportional to the dimensional accuracy. Tapper angle increases with increment salt conductivity. TSECDD material is removed in to different ways i.e. is frontal gape and lateral gape. Material is removed by EDM in frontal gape and electrochemical dissolution serves to remove material in lateral gape. Recast layer is removed by electrochemical dissolution. Better surface finish was achieved when compared with the traditional EDM.

14. Pankaj Kumar Gupta et al (2016) studied the effect of duty ratio at different pulse frequency during hole drilling in ceramics using electrochemical discharge machining. In this study, the influence of duty ratio at various pulse frequency was investigated while machining of alumina using ECDM process. Sodium hydroxide 24% wt/vol concentration was used as electrolyte cylindrical strain less steel is employed tool electrode (cathode) graphite is used as axillary electrode. with increase in duty ratio depth of penetration, MMR and heat effective zone also increases.
15. S. F. Huang et al (2014) studied the characteristic machining micro-hole in stainless steel with tool electrode high-speed rotating using ECDM. By using a micro electrode in electrochemical discharge machining micro machining can be achieved. Micro-hole is drilled in stainless by using a high-speed electrode. Pure water is used as electrode. By experimental results the empirical and mathematical modal was made. The electrode tool wear was one of the parameter which was measured. A multi-variant linear regression model is used to process independent parameter of tool wear. It was concluded that as the rotation speed of the tool increase the electrode tool wear decreases. When applied voltage is increased than tool electrode wear is decreased. When electrode diameter is increase the tool wear of electrode is decreased.
16. Ketaki Rajendra Kolhekar et al, (2016) studied the effect of electrolyte concentration on surface integrity in micro electrochemical discharge machining. It is a tedious task to machine non-conductive materials like glass at micro level. Steel block of L shape was employed as anode and tungsten rode employed as cathode. Sodium hydro-oxide is used as electrolyte as electrochemical discharge machining of borosilicate glass.

Electrolyte concentration was changed to study the influence of electrolyte concentration. 1M, 0.8M, 0.6M, 0.4M and 0.2M. Chemical etching helps to reduce the surface flaws. It was concluded that at high concentration of electrolyte the discharge energy is also high therefore, material removal is due to the vaporization of the surface. But at less concentration surface wickless were found around the periphery of the hole due to the dominance of chemical etching the surface roughness was between 2 to 3.5 micrometer. Hardness of the material surface is reduced due to bombardment of electrons at high voltage at the material surface which causing residual stress.

17. M. Sankar et al (2016), studied the effect of electrolytic concentration on the abrasive assisted- electrochemical machining of aluminum-boron carbide composite. Nonconductive materials and ceramics can be machined using electrochemical discharge machining. With increase in electrolyte concentration the material removal rate is increased but at the cost of formation of passivation layer on the machined surface. To deal with this problem the abrasive particles are mixed with the electrolyte for better surface finish. The machining of the aluminum 6061 boron carbide (5 to 15 wt.%) metal matrix composite is performed using sodium chloride as an electrolyte (10 to 30%) alone with silicon carbide abrasive particles in it. Copper is used as tool electrode for machining. Material removal increases due to increase in current density. With increase in concentration of abrasive particle in metal matrix composite the material removal rate is decrease. At 30% NaCl concentration, passivation layer is present on the surface of the material. The abrasive particles were ineffective on the passivation layer at high NaCl concentration. Extra amount of material is removed due to high concentration of NaCl. At high electrolyte concentration, the reinforcement of metal matrix is removed leaving behind the cavity which causes bad surface finish.
18. Mudimallana Goud et al (2017) studied the micromachining of quartz glass using electrochemical discharge machining. The optimization of process parameter was done for the machining of quartz glass using Taguchi standard orthogonal array with grey relational analysis for minimizing the overcut and enhancing the MMR. Graphite is employed as auxiliary electrode and stainless steel used as tool electrode. NaOH is used as electrode with 20 to 30 wt% concentration. Taguchi method with GRA is used for the optimization of both MRR and overcut. The optimum parameter for high material removal rate and less overcut are 20 wt% of NaOH concentration, 40v applied voltage and 5mm feed rate.

2.1 SCOPE OF STUDY

The science included in removing of material in electrochemical discharge machining (ECDM) is not completely evolved. The chemical action not made understandable in any article properly. The material removal extensively depends upon work piece material so with every new material the characteristics of discharge are different and therefore the material removal rate is also different. To control and reduce the flaws such as heat affected zone, overcut, micro-cracks and tempering effect are the areas in which research can be carried out. ECDM drilling with high aspect ratio is difficult to machine due to in-availability of electrolyte at the zone where the material is to be removed. This can be a major scope of study in future. In tempering effect, the tip of the tool as well as shape of tool change the material removal rate. Therefore, test with spherical electrode, negative tapered electrode and rotating tool can be done for further study.

- Effect of electrolyte flow rate on material removal rate and surface roughness for machining of Al2014/B_4C using ECDM.
- Effect of electrode gap on material removal rate and surface roughness for machining of Al2014/B_4C using ECDM.

2.2 OBJECTIVE OF STUDY

- Machining of metal matrix composite (MMC) using electrochemical discharging machining
- Optimization of the process parameters such as voltage, current and concentration of electrolyte by using Taguchi method.
- To study the effect of different the process parameters such as voltage, current and concentration of electrolyte while machining (AL 2014/ B_4C) metal matrix composite.
- To achieve more material removal rate and surface roughness.

CHAPTER 3

MATERIAL AND EXPERIMETAL SETUP

3.1 MATERIAL SELECTION

According to M. Goud et al. (2016) only 11 % of work is done on metal matrix composites. Therefore, the present work considers metal matrix composites in ECDM. Al 2014 alloy will be used as metal matrix and boron carbide (5%wt) particulates as reinforcement.

3.1.1 Aluminum

The silvery-white colored chemical element is symbolized as Al with atomic number 13. Its density is (2.6988 g/cm^3), atomic weight (26.981539), melting point (660.32 degree Celsius), and boiling point (2519 degree Celsius). This particular chemical element is mostly used in air travel as aluminum is three time lighter than steel. The studies reveal that 8% of the Earth's outer crust (by weight) is made of aluminum. Due to its low density and ability to recycle it's ranked second most widely used element in the modern scenario of science and technology.

3.1.2 The Properties of aluminum are enlisted below: -

Machining Strength Weight Corrosion resistance Nonmagnetic material Formability Conductivity Linear expansion Reflectivity

3.1.3 Aluminum series

List of aluminum series, given below throws light on its usage in the industry.

- 1000 Series: The electrical and chemical industry use primarily pure and controlled composition.

- 2000 Series: -this series contain copper as the principal element, thought other elements used magnesium is used. *2xxx* series alloys are mostly used in aircraft where they gain acceptance due to their high strengths (yield strengths as high as 455Mpa or 66 ksi).
- 3000 Series: - architectural applications and various products use demonstrate feasibility in which manganese is the principal alloying element.
- 4000 Series: - Alloy with silicon as the principal element demonstrate its occurrence in this series which reflect its utility in welding rods and brazing sheet.
- 5000 Series: - hulls, gangplanks, and other products exposed to marine environments use alloys with magnesium as main element for their materialization.
- 6000 Series: - architectural extrusions spot alloys with magnesium and silicon for their effective design.
- 7000 Series: - is contain zinc as the prominent alloying element .no doubt some more like as copper, magnesium, chromium, and zirconium also contribute to it.
- 8000 Series: - It's rare to find so it's coincided the most unusual series in the modern industry.

3.1.4 2000 series

Copper is the main alloying element in such alloys that's known for the most severe corrosion. The series has attained second place for its strength after the alloys of 7000 series. These high heats treatable aluminum alloys of the Al-Cu-Mg group takes second place the strength after the alloys of 7000 series. Its high strength and excellent performance in ballistics marked its utility in DOD in aviation and armor application. The 2000 series depicts most documented vulnerability as is the corrosion from pitting attack.

3.1.5 The Properties of 2000 series are mentioned below

- Known for its hardness.
- Remarkable strength at room and elevated temperature.
- Apt for machining.
- Hard to weld.
- Poor Corrosion resistance so needs protection.

3.1.6 Selection of 2014 Alloy

Among all different series of aluminum, we generally focused on aluminum grade 2014 due to its poor corrosion resistance and moderate strength.

- It has poor corrosion resistance
- It is used to manufacture of bodies of trucks and tractors.

Figure 3.1 Aluminum 2014 rod

3.1.7 Reinforcement

It is defined a hard phase basically made up of ceramic and used to boost up the properties of the base alloy. Boron carbide is used as reinforcement.

3.1.8 Boron carbide

It is a compound of carbon and boron with chemical formula B_4C is considered as one of the hardest black rhombohedral crystalline compounds. Since 1930 it has been the part of in-depth study world-wide. Abrasive, bulletproof vests as well as numerous industrial applications make use of it. Due to its high hardness, low density and high melting and boiling point initiate its use as reinforcing material in fabrication of composite.

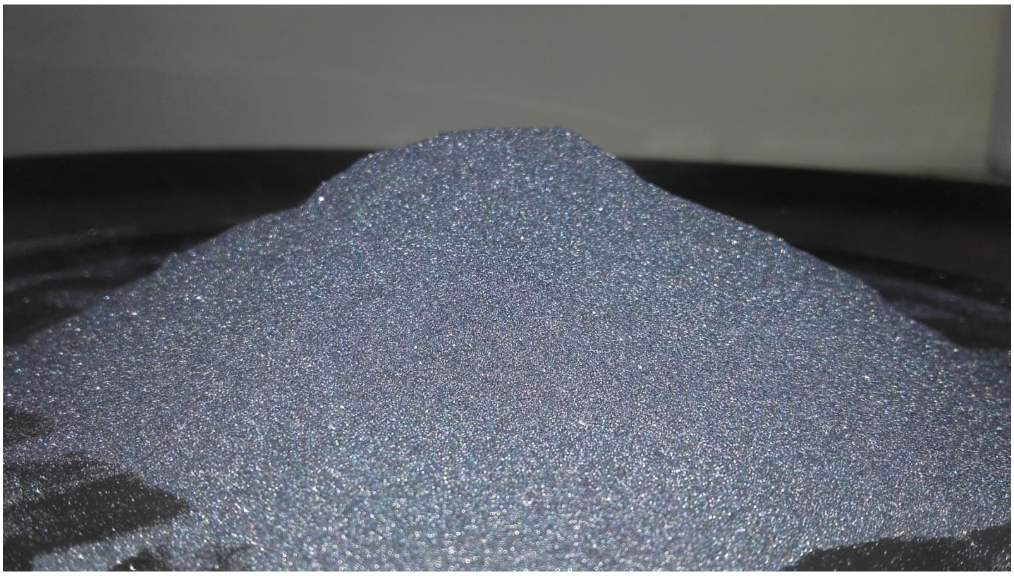


Figure 3.2 Powder of B_4C

3.1.9 The unique features of boron carbide

- good chemical resistance
- low density
- has high hardness
- Helps in minimizing the grain size of the matrix
- Improves the hardness and tensile strength of the composite

3.1.10 Application of boron carbide

- Used in the making of bullet proof vests, armor tank etc.
- Labeled as a robust material
- Helps in the materialization of Ballistic armor and nozzle in their concrete form
- Tribological element becomes effective (e.g. brake pads) due to high wear resistance
- Being a neutron absorbent, it finds its application in the nuclear industry for radioactivity containment.

3.1.11 Why do we select boron carbide as reinforcement?

- After diamond and cubic nitrite Boron carbide is known as the third hardest material
- Light ceramic material reflects robust nature.

- The lower density of boron carbide results in composites with higher specific stiffness
- Matchless thermal stability, commendable chemical interness and excellent abrasive capacity
- Wettability of B_4C particles in molten metal is the prominent trait in the fabrication of Al-B_4C composite
- B_4C also boosts impact strength.

The field of automobile, nuclear, marine, and aerospace, etc use the aluminum matrix composites abundantly. AMC's have good physical and mechanical properties e.g., low coefficient of thermal expansion, high strength, high hardness, good wear resistance and low density. B_4C powder is quite expensive that's why it's hardly used to carry out research work. Heating causes its expansion up to twice its original volume. Different directions appear differently in colors. When heated up to 16000 degree Celsiuo it gets converted into free silica and mullite. It's widely acclaimed for its good corrosion resistant properties. Different types of reinforcement are used to strengthen various properties of aluminum matrix composites. An aluminum matrix phase isn't as hard as is the reinforcement phase. Various methods like, Liquid infiltration, Powder metallurgy, Spray Deposition, Squeeze Casting, stir casting are used to fabricate the AMC's. Boron carbide powder (B_4C) powder helps to enhance the various properties of aluminum matrix composites (AMC's) through proper process parameter in order to caste a composite. The varying percentage of B_4C in the aluminum grade (2014) checks the mechanical properties at different percentage of reinforcement. Table 2 depicts the chemical composition of matrix alloy.

3.2 Composites

Composite material comprises of at least two phases i.e. matrix and reinforcement. Both vary in physical and chemical properties. They are in soluble but they get merged together to create a new stuff and this specified procedure is termed as composites. MMCs for automotive, aerospace and other structural applications have become the lucrative fields over the last five years. The outcome of availability of relative cheap reinforcements and development of various processing routes give birth to the reproducible microstructure and properties. The composites fabricated with the aluminium alloys are widely acclaimed because of their high strength, wear resistance, fracture toughness and stiffness. Aluminium metal matrix composite are categorised as light weight high performance composite materials to the demands of by suitable combinations of matrix, reinforcement and manufacturing process put forth the requirements of different applications and accordingly the properties of AMMCs are tailored. Aluminium alloy gain its wide fame due to their primarily physical and mechanical properties such as low density, high corrosion resistant etc., but their tribological properties have no demand in the field of automotive, aero plane, automobile, marine etc. Different type of reinforcement is used to promote the tribological of matrix as per our constraint.

3.2.1Types of Composite: -Different criteria categories composite material differently: -

Types of matrix material: -

1. **Metal Matrix Composites: -** The type of composite material in which one phase is made of metal and other part may be of some other metal or material is called metal matrix composites.
2. **Polymer Matrix Composites: -** The polymer matrix when combined with the fiber phase is known as polymer matrix composite.
3. **Ceramic Matrix Composites: -** Ceramic and entrenched fibers of other ceramic material combine to mark the possibility of ceramic matrix composites.

3.2.2 Shape and size of dispersed phase: -

1. Particle reinforced composites.
2. Fiber reinforced composites.
3. Structural composites.

3.2.3 Particle reinforced composites

1. Dispersion strengthened composites.
2. Particulate composites

3.2.3.1 Dispersion strengthened composite

The particles are of 0.01-0.1 micrometer in size in dispersion strengthened composite. Atomic/molecular level initiate the strengthening that visualize the mechanism of strengthening similar to that of precipitation hardening in metals. Moreover, matrix uphold the major portion of an applied load, whereas the motion of dislocations finds hindrance due to dispersions.

3.2.3.2 Particulate reinforced composite

It claims the large amounts of relatively coarse particles. These composites produce unusual combinations of properties rather than improving the strength. Concrete exemplifies the process.

Table 3.1 throws light on the Chemical Composition of matrix 2014 alloy.

Constituent	Wt.%
Al	93.5
Cu	4.4
Mg	0.8
Cr	0.1
Mn	0.6

3.3 Fabrication

Fabrication of the aluminum metal matrix composites require liquid based stir casting for its processing. The various components below used during the process are given below: -

1. Aluminum 2014 alloy
2. Boron carbide (B_4C)

3.3.1 STIR CASTING

The stir casting route is the simplest and least expensive used for mass production. The improper distribution of reinforcement in metal matrix and less wettability of reinforcement of particle with molten metal pose as major limitations.

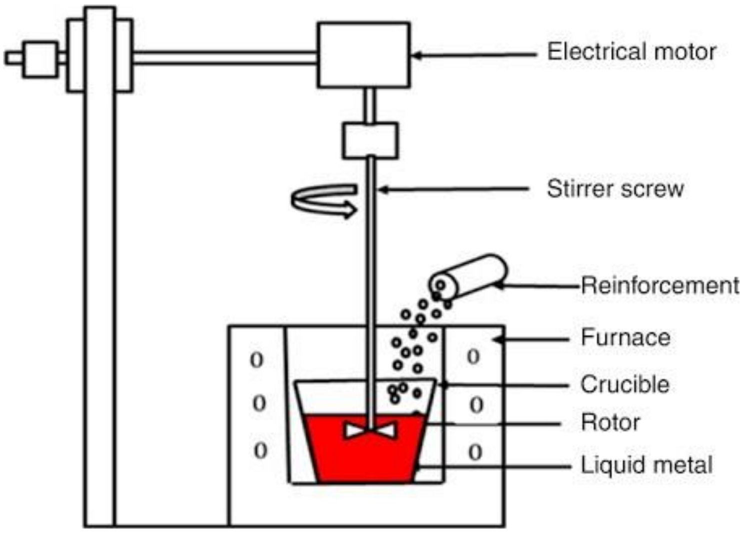


Figure 3.3 Stir casting

The hybrid types of reinforcement enhance the properties of aluminum metal matrix e.g. B_4C. The aluminum series graded matrix (2014) marks 98% purity that's why used to promote the various mechanical properties of the aluminum like tensile strength, corrosion resistance, hardness etc. Aluminum alloy 2014 rod was cut into six different pieces using power hacksaw because of its softness.

First of all the aluminum grade (2014) was melted in the furnace at 800 degree Celsius temperature and on the other side the reinforcements are preheated into the other crucible at a temperature range between 350 degree Celsius so as to enhance the wettability of B_4C particles. Argon gas is continuously supplied with the melting of aluminum alloy 2014wiyh the intension of protecting reaction between molten aluminum and the atmosphere gases.

Table 3.2 Various parameters of stir casting route

Parameters	Value
Temperature of furnace	800
Temperature of preheated of reinforcement	350
Temperature of preheated die	350
Spindle speed	500
Stirring time	6

Since stir casting process demonstrates very high temperature, experimentation becomes bit difficult and horrible. The preheated reinforcement such as boron carbide powder of 200 mesh size was transformed into the molten metal with weight percentage of boron carbide (5%) at the initial phase of fabrication of aluminum metal matrix composites. Nonstick paste is applied around the stirrer as a coating in order to avoid corrosion of the stirrer into the mixture of aluminum and reinforcement. Stirrer was placed in the muffle furnace to dry out the nonstick paste on the stirrer for about 2 hours at a temperature of 350 degree Celsius. The mixture is stirred continuously using mechanical stirrer for about 6 minutes at an impeller speed of 500 rpm to strengthen bonding between metal matrix and composite. Meanwhile, the dispersion of particle in the meltacilitated by adding, magnesium pieces to the melt.

Figure 3.4 Argon gas insert in furnace

the molten metal was poured into preheated die of 350 degree Celsius After the proper mixing of aluminum matrix with reinforcement Then solidification process of molten metal commences at room temperature. The process will be carried out time and again for remaining composition of boron carbide.

Table 3.3 Various percentage of reinforcement in stir casting

Aluminum	Boron carbide
1kg	50 g

The fabrication part is removed easily and safely from the die by polishing the internal part of the die with the nonstick graphite paint.

Figure 3.5 Cylindrical die

The ejector pin is used to remove the fabricated part from the die. Can be of any the size and shape of the fabricated part may vary. Whereas the shape of casted product depends upon the shape of die used in the process. During fabrication process of aluminum metal matrix composites, the cylindrical die of 700 gram weight and 30mm diameter finds its utility. However, in stir casting process second cylindrical die of 100 gram and 40mm diameter becomes functional. In the given figure 6, the experiment setup used in the stir casting is depicted.

Figure 3.2 Casted Cylindrical rod

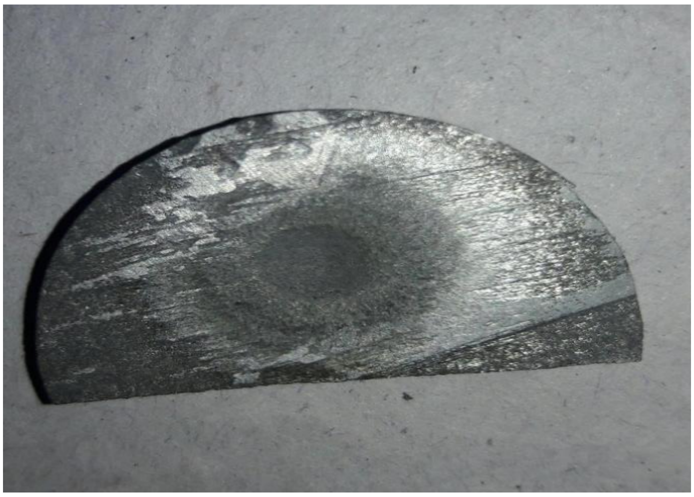


Figure 3.7 Machined Aluminum Metal Matrix

3.4 EXPERIMENTATION

The present work includes the designing of the setup for conducting experiment, selection of parameter such as machining voltage, machining current, stand of distance between electrode tool tip, pressure gap between tool and work piece and feed movement of the tool workpiece. Following components are included in the experimental setup of ECDM.

1. A pulsed D C power supply unit
2. A work piece holding arrangement unit
3. A tool holder equipment unit

4. A feeding mechanism arrangement tool feeding unit
5. A machining chamber unit

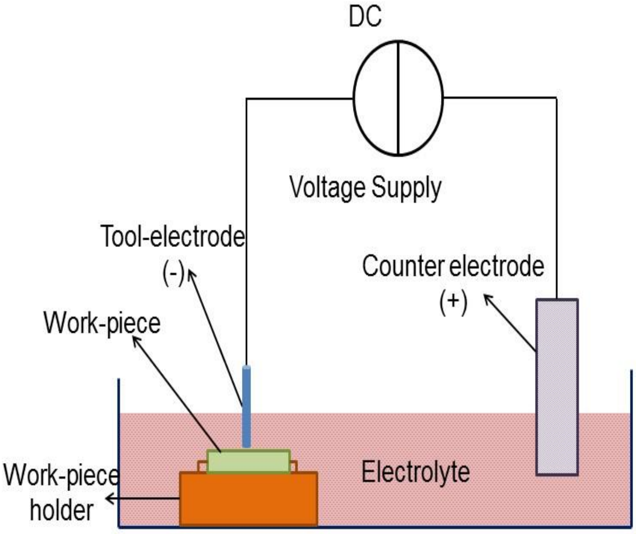


Figure 3.8 ECDM setup

1. A pulsed d.c. power unit: -a pulsed d.c. power supply consists of three phase half wave rectifier which is used to convert the ac signal into the dc signal and also used to generate the different pulsed signal from a signal dc power source. A pulsed D.C. power supply must have capability to supply the frequency of range 50HZ and also having the capability of providing voltage range of 10-80V with the step a step size of 10V.
2. A work piece holding arrangement unit:- a work piece holding arrangement must have the fixed support which used to hold the work piece tightly so that there is no looseness of work piece during the cutting operations.
3. A tool holder equipment unit: - It is the device which is used to hold the tool and also used to provide the tool movement.
4. Manual tool feeding unit: - Manual feeding mechanism arrangement for tool feeding arrangement is used to provide the feed of tool against the work piece and it is also used to provide the movement of tool. Different feeding mechanism used to feed the tool for example, gravity feed mechanism. In this experiment two bolts and four nuts are used for tool feeding.
5. Machining chamber: - A machining chamber is used to carry the electrolyte which is provide the working medium of cutting process i.e. it is chamber where the all the cutting operation is being carried out.

3.5 Electrolyte

It is a particular kind of matter which when dissolved in a polar solvent, like water, it acts like an electrically conducting solution. Cations and anions uniformly disperse in the polar solvent. Sodium chloride is used as electrolyte. Sodium chloride is also called salt. It is an ionic compound and represented by the chemical formula NaCl, with a 1:1 ratio of Na and Cl ions. It has molar masses of 22.99 and 35.45 $g \cdot mol^{-1}$, respectively, 100 g of NaCl contain 39.34 g Na and 60.66 g Cl.

3.6 Electrode

It is an electrically conducting material which makes contact with the noncontacting part of the circuit. Tool electrode used is copper with cylindrical diameter of 3mm and spherical diameter of 2.5mm and steel is used as auxiliary electrode of 4mm diameter.

Figure 5.9 Copper electrode

3.7 TAGUCHI PARAMETER DESIGN

Design of experimental technique of standard Taguchi methodology is exploited to perform the experiments conceitedlys is formed using. The design of experiment is drafted in a way to form. a matrix composed of variantlevels of variable parameter. This method defines the variant levels of variable parameters so as to minimise the number of experiments to be conducted. Therefore, within short span and limited resources the optimization of the design parameters is attained.

3.7.1 Procedure for applying Taguchi technique

1. Problem formulation

A problem is first identified. Then the information is sought based on the facts and figures. After setting the objectives, a framework of experiments is designed. The controllable parameters or signals e.g. the process parameters are determined. These signals evaluate the performance of the process. There may be some unmanageable parameters influencing the performance of the process thereby causing nuisance. Certain environmental factors like vibrations, temperature, humidity etc are considered to influence the performance of the machine. The limits of low and high values of parameters are termed as levels. Optimization of parameters is attained by combining controllable parameters at different levels for experiment work.

2. Experimental design

Experimental design uses orthogonal array. The controllable parameters and number of level of controllable parameters selected to serve the desired purpose influence the choice of orthogonal array. Three controllable factors and their 3 levels are undertaken to conduct the research. For such design of experiment L9 is considered to be the apt one. It offers 9 combinations of parameters. In case of the Taguchi orthogonal array, only the most affecting nine parameter combinations display their capability. This saves time and energy. Moreover, it proves to be the fruitful method.

3. Analysis of results

Signal-to-noise (S/N) ratio and analysis of Variance (ANOVA) are the techniques to determine the authenticity of the experimental procedure. The governable parameters are known as signals and noise that’s an ungovernable parameter. The variance is analyzed by ANOVA analyze the variance. The analysis of the variance method finds the foremost method.

4. Experimental Validation

The last step conforms the results. There are 9 parametric combinations observed in designing of experiment. Optimum results are given only by one out of 9 experiments. Various factors create plot for comparison. Now the result gives the best effective parametric variable an additional experiment compares the experimental and the actual result using these parametric variables.

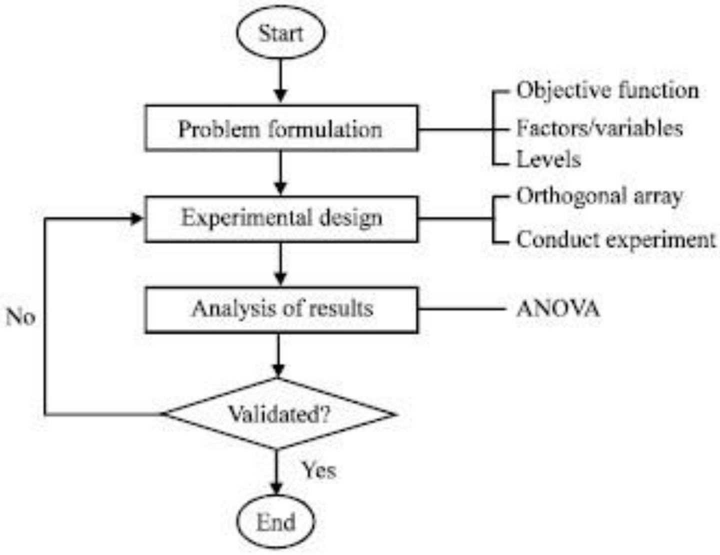


Figure 3.10: Procedure and steps of Taguchi parameter design

3.7.2 Ratio of signal to noise:

Taguchi method lessens the variability of the product. Noise, the effects of uncontrollable parameters are minimised to notice controllable parameters. Controllable parameters can be controlled as process parameters. Noise factor can be controlled only after performing experiment. The technique ensures the variability of the noise parameters. Whereas for optimization, the control factor settings are minutely studied and optimised to get the robust product. The Taguchi process helps in procuring higher signal-to-noise (S/N) values which spot control factor settings to minimise the effects of noise factors.

The Taguchi process comprises of 2 steps mentioned below:

Step 1: The optimum controllable parameter is procured using the signal-to-noise (S/N) ratio to minimise the variability.

Step 2: The control factors with least effect on signal-to-noise (S/N) ratio are spotted as.

They bring the mean values closer to the target.

The target values vary as per the changing noise conditions and these values are evaluated by signal-to-noise (S/N) ratio. Different signal-to-noise ratios may be adopted to hit the target of the experiment.

The static experiments make use of four different signal-to-noise ratios:

(1) Larger is better:

The specified signal-to-noise ratio maximizes the response.

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

(2) Nominal is best (default):

This particular signal-to-noise ratio fixes and deduces the response. Deviations and mean foundation.

$S/N = 10 \times \log((\bar{Y}^2) \div \sigma^2)$

(3) Smaller is better:

To minimize the response the following signal-to-noise ratio depicts its utility.

$S/N = -10 * \log(\Sigma(Y2)/n))$

3.8 ANOVA (ANALYSIS OF VARIANCE)

The research conducted uses ANOVA (Analysis of Variance) in two ways with two or more different variables and their quantitative results. Two-way ANOVA marks its success under various conditions. Two or more independent variables used via this methodology may or may not affect each other. The structural pattern of two-way ANOVA demonstrates each categorical variable with its own population mean. This Interaction model hardly bears any restrictions on its patterns. On the contrary, the non-interaction (additive) model conforms restriction on its population mean. The limitations imposed finds out that the effect on the outcome of one explanatory variable is similar to that of every other explanatory variable. They all enjoy independency. It is termed as Additive model. No doubt in case of the Interaction model the level change of one variable depends on the levels of other variables.

3.8.1 Interpretation of the key results for two-way ANOVA:

Step 1: Determining as if the main effects and interaction effect are statistically relevant: -

- In order to determine the above-mentioned impact, compare the p-value for each term is compared to the significance level so as to ascertain the null hypothesis. As per studies, the significance level (denoted as α or alpha) of 0.05 serves the purpose. A significance level of 0.05 denotes 5% risk of concluding that an effect occurs where there is nothing of the kind in actuality.
- The response mean for all factor levels shows equality as a result of the null hypothesis for a main effect.
- The null hypothesis for an interaction effect highlights that the response mean for the level of one factor has no co-relation with the value of the other factor level.
- The p-value influences the statistical relevance of the effect as given below:
- In case of higher p- value than the significance level settled, the effect won't be statistically important.
- However, if p-value is less than or equal to the significance level settled, then the effect for the term is found to be statistically important.
- The points given below reveal how to interpret important interaction effects and main effects.
- The gap between some of the factor level means is statistically worth mentioning if the main effect of a factor is important.
- In case of statistically relevant interaction significant, the bond between a factor and the response varies by varying the level of the other factor. The main effects shouldn't be interpreted without taking into account the interaction effect.

Step 2: Evaluate the means

The means table is referred to acknowledge the group variations in case p-value value in the

ANOVA table figures out a statistically important main effect or interaction effect.

The table illustrates the groups within each factor and their fitted means to produce the main effects. To get interaction effects, the table marks all the possible assimilation of groups across both factors.

Step 3: Ascertain how well the model fits your data

Let’s examine the goodness-of-fit statistics in the model summary table to know how well the model fits the supplied data.

S is used to know how well the model extracts the response. Thus, S is the response variable that presents the standard deviation to predict f how far the data values fall from the fitted values. The lower the value of S, the better the model describes the response. Comparing different models, the model with the lowest S value has been found to be the best fit.

R-sq

- R2 reflects the percentage of variation in response to the mode explained. Higher value of the R2 enables the data to be fitted in a better way. R2 ranges between 0% and 100%.
- R2 shoots up after some additional predictors get associated with a model. For instance, the most effective five-predictor model will always possess an R2 i.e. at least as high the best four-predictor model. Therefore, R2 is most acceptable in terms of popularity and usability while comparing with the models of the same size.

A high R2 value guarantees the matching of the model with the model assumptions. The residual plots needs to be checked in order to verify the assumptions.

R-sq (adj)

- The adjusted R2 is used while comparing models with others that having different numbers of predictors. R2 always rises with the addition of a predictor to the model, even if it shows no improvement at all. The adjusted R2 value is quite beneficial at the time of choosing the correct model after incorporating the number of predictors in the model.

R-sq (pred)

- The predicted R2 assists to determine the response for new observations effectively. Larger predicted R2 values, is the predictive ability.
- If the predicted R2 is lower than R2, it indicates that the model turns out to be over-fit. When the terms for effects are added which have no significance in the population, the over-fit model comes to light though they could be considered for the sample data. The model becomes accustomed to the sample data thereby lose its identity for making predictions about the population.
- Predicted R2 is more fruitful than the adjusted R2 for comparing models for the calculations derived for the observations are not the part of the model calculation.

3.9 MECHANICAL CONTACT PROFILER

Mechanical contact profiler is used to analyse the surface roughness. Surface roughness was examined with the help of profiler's conical diamond tip stylus. The angle of diamond tip varies from 60 to 90 and radius of tip is also varying from 1 to 10 µm. The motion of tip of mechanical profiler is in linear motion which ranges from 1 to 10 mm and the direction of motion is perpendicular to the direction of machining. It gives the various value like R_A, R_Z, R_Q, R_T, R_P, and R_{PC}. But in this study only Ra value is required to examine the surface roughness to optimized the machining parameter. During the working of stylus there is no external force and the disturbance acting on the stylus. It moves over the workpiece surface with the constant speed and it is a two ways motion forward and backward motion. There is a transducer that reads the vertical variation of the stylus tip and converts the mechanical signal to the electrical signal. There is amplifier that converts the analog signal into digital signal. Further these digital signals are processed by computer to check roughness and surface waviness. The advantage of mechanical profiler is that it is portable and easy to use. For this thesis work Taylor-Hobson Talysurf surface profiler is used.

Figure 3.11: Surface roughness of aluminium boron carbide by using Mechanical contact profiler

CHAPTER 4

RESULT AND DISCUSSION

4.1 TAGUCHI METHOD

The Taguchi method has been used quite successfully in several industrial applications to optimize manufacturing processes and in the design of electrical and mechanical components. Taguchi’s method helps to find the best set of specified process parameter level combinations which include the discrete setting values of the process parameters. Further S/N ratio and mean plots are used to find the optimal values for cutting and the geometric parameters. S/N ration consist of two variables known as controllable and uncontrollable also known as signal and noise respectively. In order to find optimal parameter, the value of S/N ratio should be high for which there must be reduction in uncontrollable factors.

4.2 RESULT ANALYSIS

In this section of this chapter the results for finishing machining i.e. Surface Roughness and material removal rate is discussed. As discussed in chapter 3, experiment are performed by varying the parameters that are voltage, electrolyte concentration, current respectively, in order to machine particulate reinforced metal matrix composite (Al2014/B_4C) by using copper as tool electrode and steel as auxiliary electrode in ECDM. Sodium chloride is used as electrolyte. The experiments are performed on the basis of Taguchi design. The results obtained from the experimental investigation for Surface Roughness (Ra) and material removal rate are shown in Table. These results obtained and then used to develop a relationship between the surface roughness, MMR and process variables on the basis of signal to noise ratio by depicting graph between them.

4.2.1 TAGUCHI DESIGN

Using Taguchi design different levels of process parameters are generated, which are to be used for performing the experimental work, which are then analysed using signal to noise ratio. In this study L9 orthogonal array is used for attaining optimal result is calculated with good confidence level. Where these process parameters get affected by two factors known as controllable and uncontrollable also known as signal and noise respectively. Thus, with the help of S/N ratio we can found which are the parameters which are less affected by noise and can be easily controlled. Henceforth model developed is satisfactory to signify the relation between machining parameters and surface roughness, MMR.

Design of Experiment for cutting parameters

- Select Process Factors with Respective Levels
- Select Parameters to Optimize
- Conduct Experiments according to DOE
- Formulate Observed Responses in DOE Table

- Taguchi Design optimization

- Model Significance
    - Mean Ratio Plot
    - S/N Ratio Plot

Figure 4.1: System procedure for optimized the machining parameter

4.2.2 DESIGN OF EXPERIMENT FOR MACHINING PARAMETERS

Table 4.1: Selected Process Factors/Levels for Optimizing Machining Parameters

FACTORS/LEVEL	UNITS	I	II	III
ELECTROLYTE CONCENTRATION	%	15	17.5	20
VOLTAGE	V	60	70	80
CURRENT	A	6	7	8

Table 4.2: Selected Process Factors with Respective Levels

S.no	Electrolyte concentration (%g/ml)	Voltage (V)	Current (C)
1	15	60	6
2	15	70	7
3	15	80	8
4	17.5	60	7
5	17.5	70	8
6	17.5	80	6
7	20	60	8
8	20	70	6
9	20	80	7

After getting the desired level of combinations of considered parameters, we have to perform our experimental work according to the value that are generated with the help of Taguchi L27 as discussed in table 4.2. Our experiment is to perform electrochemical discharge machining of aluminium matrix composite. After performing the whole experiment according to the Taguchi L27 array next step is to optimize the parameters for achieving the good surface finish and more MMR which is discussed in next section.

Table 4.3: Experimentally Calculated Results

S.no	Electrolyte concentration (%g/ml)	Voltage (V)	Current (C)	MMR	surface roughness
1	15	60	6	1.08	1.3991
2	15	70	7	1.72	1.7727

3	15	80	8	1.81	1.9466
4	17.5	60	7	1.40	1.4550
5	17.5	70	8	1.82	1.6134
6	17.5	80	6	1.91	1.7866
7	20	60	8	1.55	2.0347
8	20	70	6	1.70	1.9031
9	20	80	7	1.95	1.4832

4.2.3 TAGUCHI DESIGN OPTIMIZATION FOR PARAMETERS

In order to get best result for better surface finish and more material removal rate the results have to be analysed for which signal to noise ratio is being used, which works on the basis of L27 orthogonal array where S/N ratio gets affected by two factors controllable and uncontrollable. Controllable factors are also known as signal and can be controlled easily, whereas uncontrollable are known as noise which are to be minimized in order to identify control factors that decreases the variability in the products. In this way signal to noise ratio identifies the optimal factors mean these are the factors which has less effect on S/N ratio in order to reduce variability means bringing values closer to the target. The following table shows values for mean and S/N ratio for surface roughness, which is achieved experimentally by conducting turning operation on different levels of parameters.

Table 4.4: Table for S/N Ratio

S.no	Electrolyte concentration (%g/ml)	Voltage (V)	Current (C)	MMR (mg/min)	surface roughness (µm)	SNRA for MMR	SNRA2 surface roughness
1	15	60	6	1.08	1.3991	0.66848	-2.91698
2	15	70	7	1.72	1.7727	4.71057	-4.97270
3	15	80	8	1.81	1.9466	5.15357	-5.78553
4	17.5	60	7	1.40	1.4550	2.92256	-3.25726

5	17.5	70	8	1.82	1.6134	5.20143	-4.15484
6	17.5	80	6	1.91	1.7866	5.62067	-5.04055
7	20	60	8	1.55	2.0347	3.80663	-6.17001
8	20	70	6	1.70	1.9031	4.60898	-5.58923
9	20	80	7	1.95	1.4832	5.80069	-3.42399

Surface roughness is calculated at the hole created. In order to get optimal factors for attaining the good surface finish Minitab 17 software is used, which helps in getting optimal results. In this table, at different combinations of voltage, electrolyte concentration, current value of surface roughness (Ra) and MMR is checked. Now, by inputting all these values in Minitab 17 we have calculated what will be the mean of surface roughness, MMR and values for signal to noise ratio of surface roughness, MMR. The approach that is to be used for calculating the values and graphs for mean is smaller is better and for surface roughness graphs for mean larger is better. S/N ratio is calculated using $-10\log1/n\ (\sum Y i^2)$. It is to be noted only that factor is considered as optimal factor for which S/N ratio value is high and this can only be achieved if value of signal is greater than noise means by lowering the effect of the noise we can control the controllable factor also known as signal. On, the basis of these value of mean and S/N ratio graphs are being generated by Minitab 17, which shows that what are the optimal parameters for achieving good surface finish and more MMR while machining of MMC.

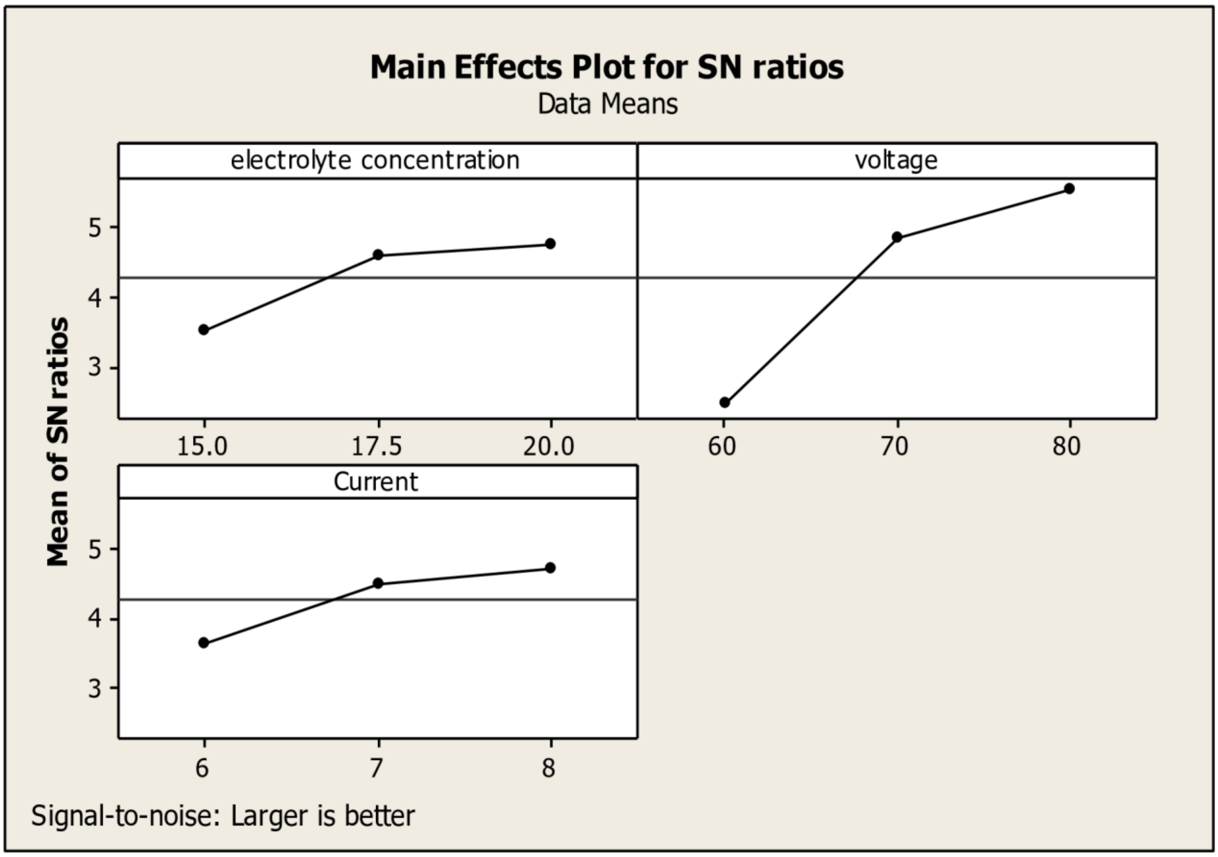


Figure 4.2: Graph for Main Effects Plot for SN ratios for MMR

The above figure depicts the SN ratio plot in which the horizontal line is the value of the total mean of the SN ratio. Larger the value of mean better is the quality characteristics for the material. As per the analysis of means from graph the levels of parameters which are to be set for getting optimum value for more MRR are of voltage (80), electrolyte concentration (20), and current (8).

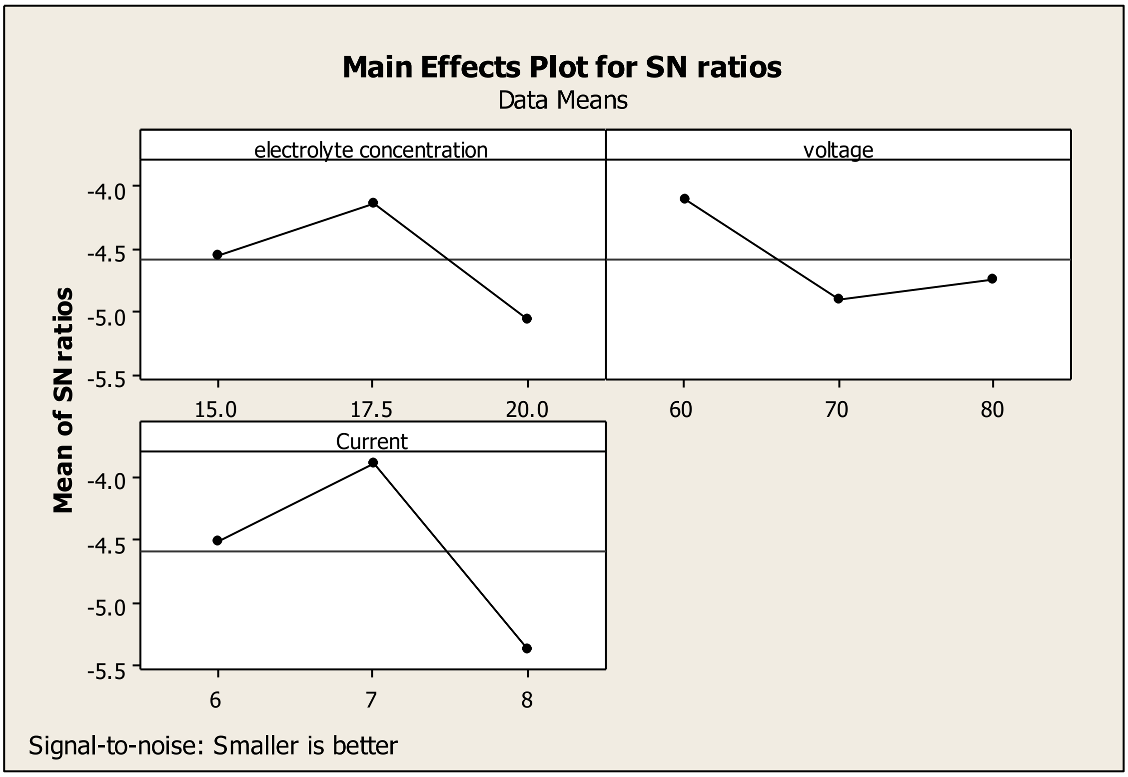


Figure 4.3: Graph for Main Effects Plot for SN ratios for surface roughness

The above figure depicts the SN ratio plot in which the horizontal line is the value of the total mean of the SN ratio. Larger the value of mean better is the quality characteristics for the material. As per the analysis of means from graph the levels of parameters which are to be set for getting optimum value for good surface finish are voltage (60), electrolyte concentration (17.5), and current (7).

4.3 Analysis of variance (ANOVA)

Table 4.5: ANOVA of variance for MRR

Source	DF	Seq ss	Adj SS	Adj MS	F-Value	P-Value	Percentage Contribution %
Electrolyte concentration	2	0.06927	0.06927	0.03463	3.36	0.0229	11.62
voltage	2	0.48207	0.48207	0.24103	23.40	0.0041	80.90
current	2	0.04407	0.04407	0.02203	2.14	0.0319	7.40
Error	2	0.02060	0.02060	0.01030			
Total	8	0.61600					
S= **0.101489**		r-sq= 96.66%	r-sq (adj)= 86.62				

4.3.1 ANOVA of variance for MRR

The confidence level for all intervals is kept as 95 indicates a 5% risk of concluding that an effect exists when there is no actual effect i.e., p- value should be less than 0.05.

If p-value is less than 0.05 it shows doubt on null hypothesis, which says all sample means equal and effect of that factor on the result is statistically significant.

From the above ANOVA table, we can see that the most significant factor is voltage. It percentage contribution is 80.90% followed by electrolyte concentration contributing 11.62% The least significant factor is current, contributing only 7.40%.

In ANOVA results, the predictors explain 99.66% of the variation in the response. The adjusted R2 is 86.62%. The lower the value of S, the better the model describes the response, it is found to be 0.101489.

Table 4.6: ANOVA of variance for surface roughness

Source	DF	Seq ss	Adj SS	Adj MS	F-Value	P-Value	Percentage Contribution
Electrolyte concentration	2	0.0535	0.0535	0.0267	.25	0.045	25
Voltage	2	0.0303	0.0303	0.0152	.14	0.042	14
Current	2	0.1311	0.1311	0.0655	.61	0.031	61
Error	2	0.2760	0.2760	0.1080			
Total	8	0.4309					
S=**0.328671**		r-sq= 49.87%	r-sq (adj)= 0.00%				

4.3.2 ANOVA of variance for surface roughness

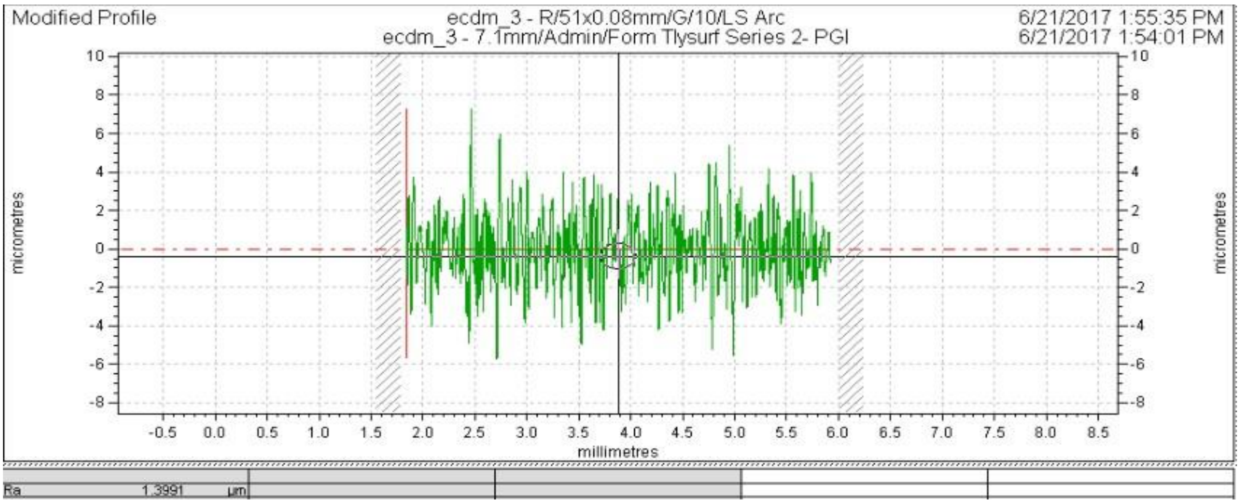
The confidence level for all intervals is kept as 95 indicates a 5% risk of concluding that an effect exists when there is no actual effect i.e., p- value should be less than 0.05. If p-value is less than 0.05 it shows doubt on null hypothesis, which says all sample means equal and effect of that factor on the result is statistically significant.

From the above ANOVA table, we can see that the most significant factor is current. It percentage contribution is 61% followed by Electrolyte concentration contributing 25%.

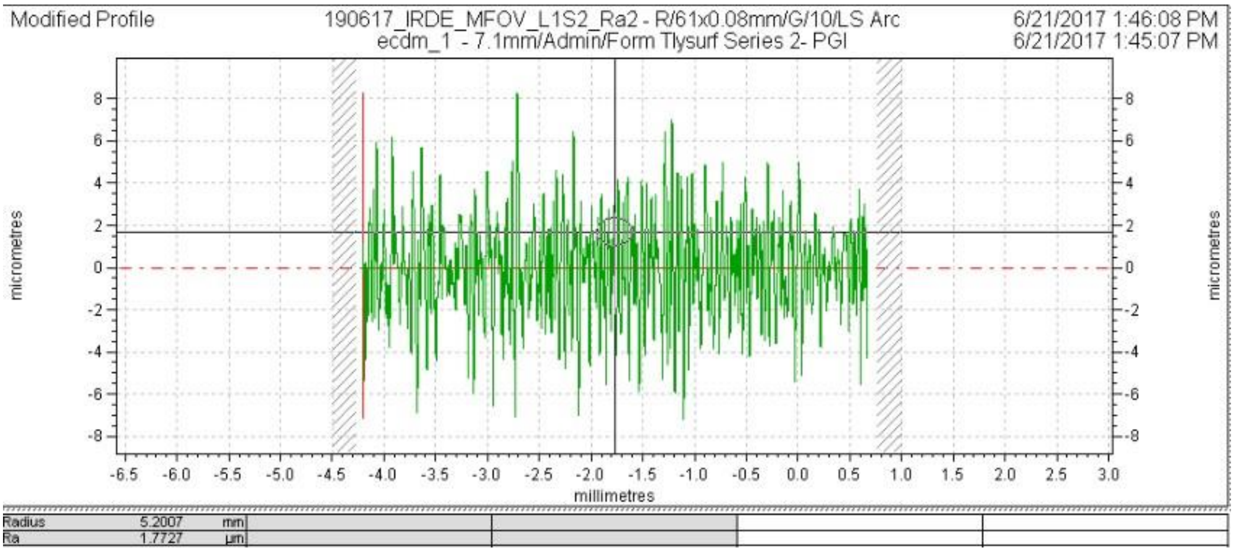
The least significant factor is voltage, contributing only 14%.

In ANOVA results, the predictors explain 49.87% of the variation in the response. The adjusted R2 is 0%. The lower the value of S, the better the model describes the response, it is found to be 0.328671

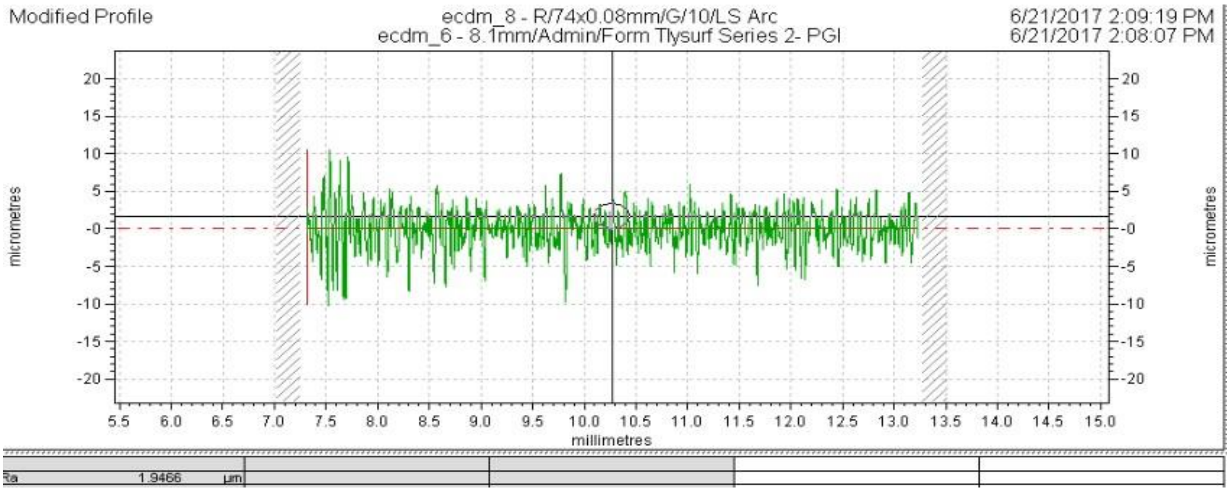
4.4 SURFACE ROUGHNESS GRAPH



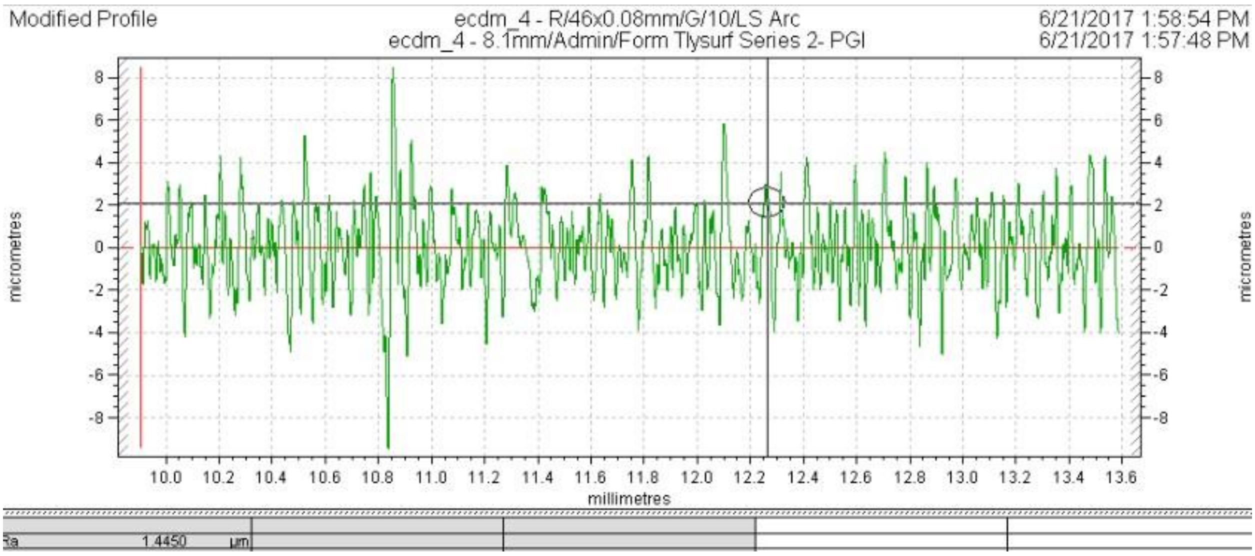
Ra 1.3991 µm



Radius 5.2007 mm
Ra 1.7727 µm



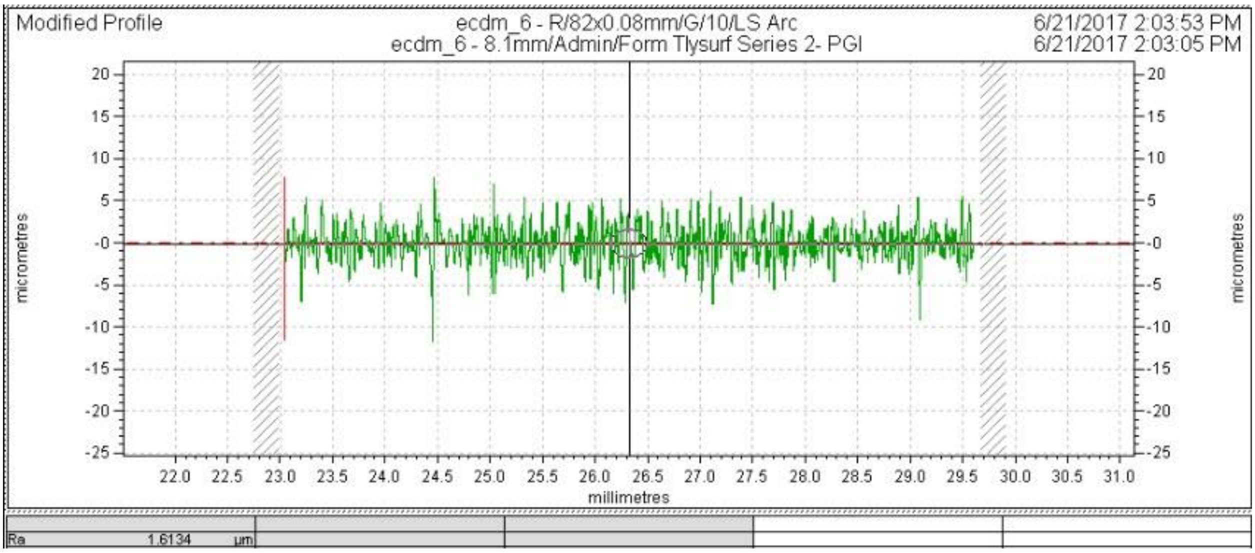
Ra 1.9466 µm


Modified Profile

ecdm_4 - R/46x0.08mm/G/10/LS Arc
ecdm_4 - 8.1mm/Admin/Form Tlysurf Series 2- PGI

6/21/2017 1:58:54 PM
6/21/2017 1:57:48 PM

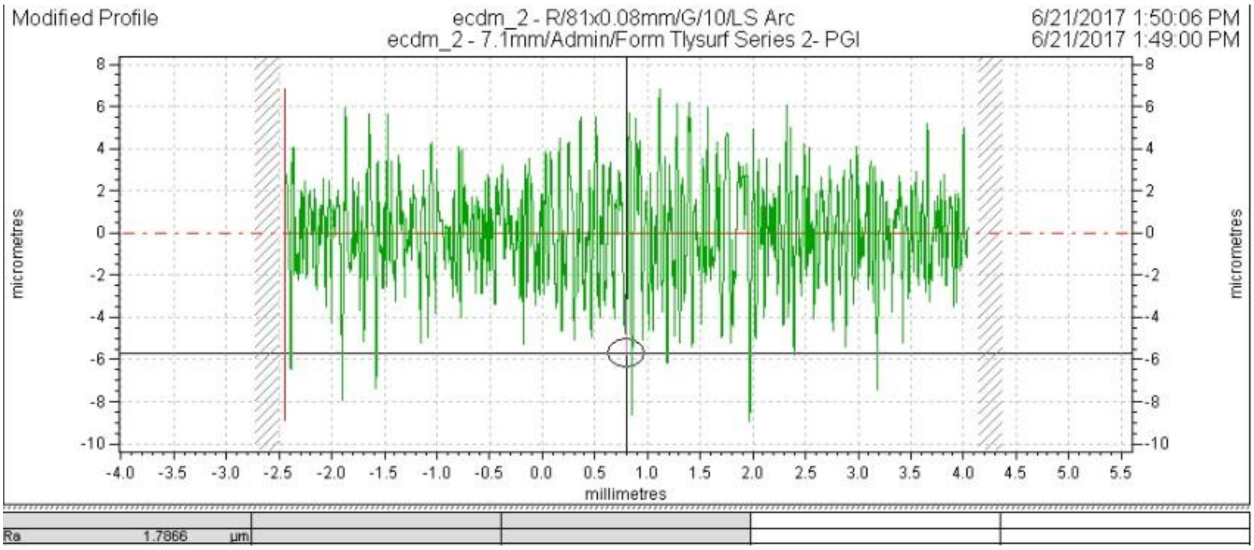
Ra 1.4450 µm


Modified Profile

ecdm_6 - R/82x0.08mm/G/10/LS Arc
ecdm_6 - 8.1mm/Admin/Form Tlysurf Series 2- PGI

6/21/2017 2:03:53 PM
6/21/2017 2:03:05 PM

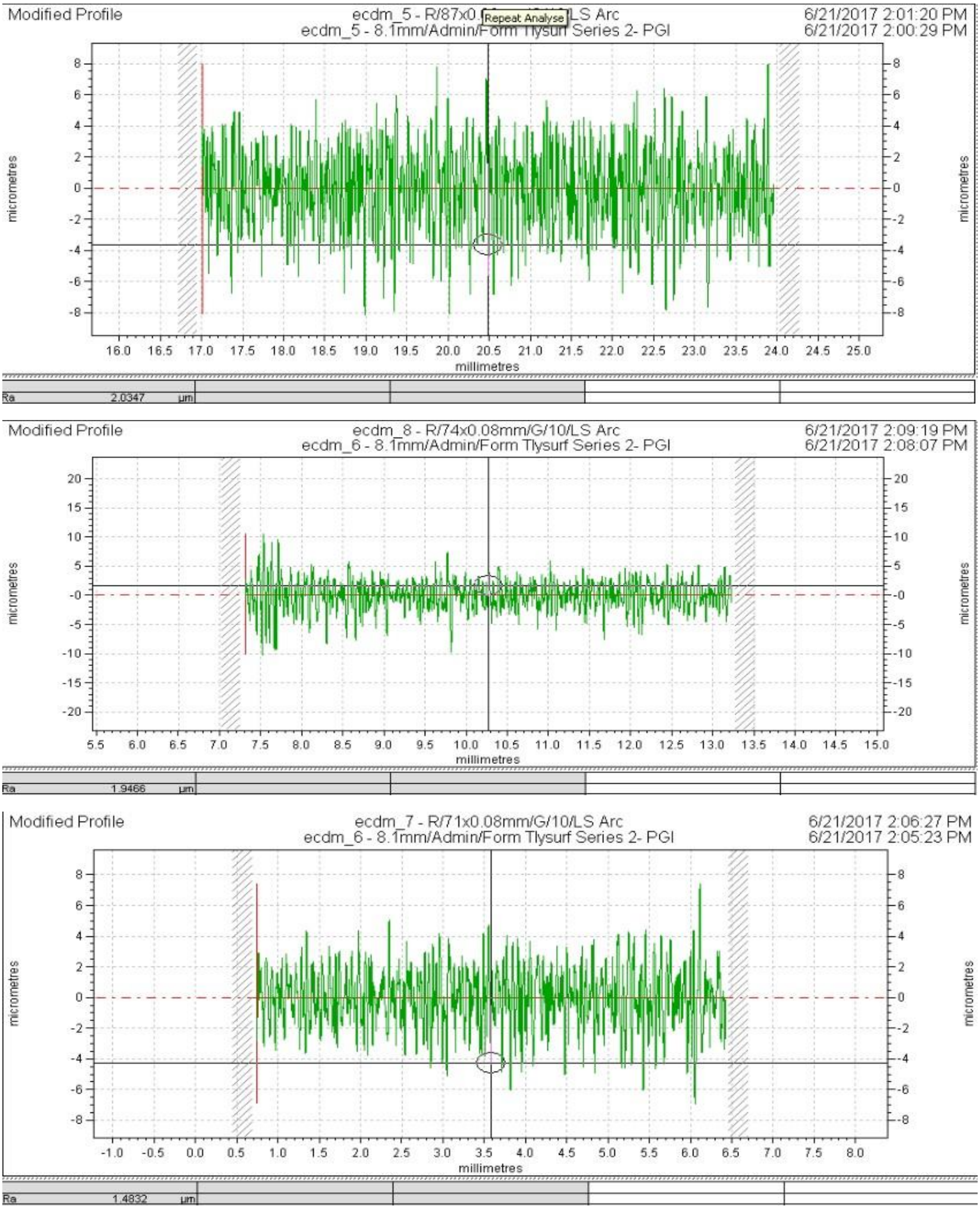
Ra 1.6134 µm


Modified Profile

ecdm_2 - R/81x0.08mm/G/10/LS Arc
ecdm_2 - 7.1mm/Admin/Form Tlysurf Series 2- PGI

6/21/2017 1:50:06 PM
6/21/2017 1:49:00 PM

Ra 1.7866 µm



Ra 2.0347 µm

Ra 1.9466 µm

Ra 1.4832 µm

Figure 4.4: Surface roughness graph

CONCLUSION

1. The optimised machining parameters for machining of aluminium metal matrix particulate reinforced by 5% of boron carbide for more MRR are of voltage (80), electrolyte concentration (20), and current (8).
2. Voltage was found to be the most significant factor affecting MRR followed by electrolyte concentration and current respectively during the machining.
3. The optimised cutting parameters machining of aluminium metal matrix particulate reinforced by 5% of boron carbide for good surface finish are voltage (60), electrolyte concentration (17.5), and current (7).
4. Current was found to be the most significant factor good surface finish followed by electrolyte concentration and voltage respectively during the machining.
5. With increase in voltage, electrolyte concentration and current the material removal rate increases.
6. With increase in electrolyte concentration the surface roughness decreases. But at 20% of electrolyte concentration due to the accumulation of debris in the machining gap unstable arc is produced.
7. With increase in voltage the surface roughness decreases.
8. With increase in current the surface roughness decreases. But at 6A unstable arc is produced therefore causing poor surface finish.

REFERENCES

1. Kamaraj, A. B., Jui, S. K., Cai, Z., and Sundaram, M. M. (2015), *"A mathematical model to predict overcut during electrochemical discharge machining"*, International Journal of Advanced Manufacturing Technology, Vol. 81, 1-4, pp. 460-691.
2. Zhang, Z., Huang, L., Jiang, Y., Liu, G., Nie, X., Lu, H., and Zhuang, H. (2016), *"A study to explore the properties of electrochemical discharge effect based on pulse power supply"*, International Journal of Advanced Manufacturing Technology, Vol. 85, 9-12, pp. 2107-2114.
3. Yang, C. K., Wu, K. L., Hung, J. C., Lee, S. M., Lin, J. C., and Yan, B. H. (2011)*, "Enhancement of ECDM efficiency and accuracy by spherical tool electrode",* Transactions-American Society of Mechanical Engineers Journal of Engineering for Industry, Vol. 51, 6, pp. 528-535.
4. Liu, J. W., Yue, T. M., and Guo, Z. N. (2010),*"An analysis of the discharge mechanism in electrochemical discharge machining of particulate reinforced metal matrix composites*", *International Journal of Machine Tools and Manufacture*, Vol. 50,1, pp. 86-96.
5. Sivaprakasam, P., Hariharan, P., and Gowri, S. (2013), *"Optimization of micro-WEDM process of aluminum matrix composite (A413-B_4C): a response surface approach"*, Materials and Manufacturing Processes, Vol. 28, 12, pp. 1340-1347.
6. Chak, S. K., and Rao, P. V. (2007), *"Trepanning of Al_2O_3 by electro-chemical discharge machining (ECDM) process using abrasive electrode with pulsed DC supply"*, *International Journal of Machine Tools and Manufacture*, Vol. 47, 14, pp. 2061-2070.
7. Han, M. S., Min, B. K., and Lee, S. J. (2011*), "Micro-electrochemical discharge cutting of glass using a surface-textured tool"*, CIRP Journal of Manufacturing Science and Technology, Vol. 4, 4, pp. 362-369.
8. Patil, N. G. and Brahmankar, P. K. (2010), *"Determination of material removal rate in wire electro-discharge machining of metal matrix composites using dimensional analysis",* International Journal of Advanced Manufacturing Technology, Vol. 51, 5-8, pp. 599-610.

9. Liu, J. W., Yue, T. M., and Guo, Z. N. (2009), *"Wire electrochemical discharge machining of Al2O3 particle reinforced aluminum alloy 6061"*, Materials and Manufacturing Processes, Vol. 24, 4, pp. 446-453.
10. Satishkumar, D., Kanthababu, M., Vajjiravelu, V., Anburaj, R., Sundarrajan, N. T., and Arul, H. (2011), *"Investigation of wire electrical discharge machining characteristics of Al6063/SiCp composites"*, International Journal of Advanced Manufacturing Technology, Vol. 59, 9, pp. 975-986.
11. Goud, M., Sharma, A. K., and Jawalkar, C. (2016), *"A review on material removal mechanism in electrochemical discharge machining (ECDM) and possibilities to enhance the material removal rate"*, Precision Engineering, Vol. 45, pp. 1-17.
12. Zhang, Y., Xu, Z., Zhu, Y., and Zhu, D. (2016). *"Machining of a film-cooling hole in a single-crystal superalloy by high-speed electrochemical discharge drilling"*. Chinese Journal of Aeronautics, Vol 29, 2, pp. 560-570.
13. Zhang, Y., Xu, Z., Zhu, D., and Xing, J. (2015). *"Tube electrode high-speed electrochemical discharge drilling using low-conductivity salt solution"*. International Journal of Machine Tools and Manufacture, Vol 92, pp. 10-18.
14. Gupta, P. K., Bhamu, J. P., Rajoria, C. S., Lautre, N. K., and Agarwal, V. (2016). *"Effect of Duty Ratio at Different Pulse Frequency during Hole Drilling in Ceramics Using Electrochemical Discharge Machining"*. MATEC Web of Conferences, Vol 77, pp. 10004).
15. Huang, S. F., Liu, Y., Li, J., Hu, H. X., and Sun, L. Y. (2014). *"Electrochemical discharge machining micro-hole in stainless steel with tool electrode high-speed rotating"*. Materials and Manufacturing Processes, Vol 29, 5, pp. 634-637.
16. Kolhekar, K. R., and Sundaram, M. (2016). *"A Study on the Effect of Electrolyte Concentration on Surface Integrity in Micro Electrochemical Discharge Machining"*. Procedia CIRP, Vol 45, pp. 355-358.
17. Sankar, M., Gnanavelbabu, A., Rajkumar, K., and Mariyappan, M. (2016). *"Electro Chemical Machining of Aluminum-Boron Carbide-Nanographite Composites"*. Applied Mechanics and Materials, Vol. 852, pp. 136-141.

18. Goud, M., and Sharma, A. K. (2017). *On performance studies during micromachining of quartz glass using electrochemical discharge machining*. Journal of Mechanical Science and Technology, Vol 31, 3, pp. 1365-1372.