Experimental Investigation and Optimization of EDM Process Parameters on Machining of Aluminum Boron carbide (Al-B$_4$C) Composite

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in

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Submitted By

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CERTIFICATE

This is to certify that thesis entitled **"Experimental Investigation and Optimization of EDM Process Parameters on Machining of Aluminum Boron carbide (Al-B_4C) Composite"** submitted by **Mr. Ravi Parkash** in partial fulfillment of the requirements for the award of master of technology in mechanical engineering with "Production Engineering" specialization during session 2012-2014 in the Department of Mechanical Engineering Delhi Technological University, Delhi.

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

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ABSTRACT

Productivity and quality are two important parameters which have great concerns in today's competitive global market. All the production/manufacturing units mainly concentrate on these two issues. In last decade manufacturing capabilities of machine tool industry has grown exponentially but still they are not utilized at their full potential. This limitation is due to failure to use these machine tools at their optimum operating conditions.

In non-conventional machining processes like EDM, the most important aspect is the selection of optimum level of process parameters to obtain best output. The materials which can be easily machined by EDM process are composites, carbides, ceramics, heat treated tool steels, super alloys, heat resistant steels etc. The Al metal matrix composites (AMMCs) is extensively used in aerospace, automotive and military industries due to their high strength to wear ratio, good wear resistance, light weight, high specific stiffness, and low coefficient of thermal expansion. The reinforcing particles used in the composite material are carbides (SiC, TaC, WC, B_4C), nitrides (TaN, ZrN, Si_3N_4, TiN), borides (TaB_2, ZrB_2, TiB_2, WB) and oxides (ZrO_2, Al_2O_3, ThO_2). Boron carbide (B_4C) is a good substitute to Al_2O_3 and SiC due to its high hardness (the third hardest material after diamond and boron nitride), high strength, low density (2.52 g/cm^3), good wear resistance and good chemical stability.

In the present work, Al 6061 alloy is used as a base metal which is reinforced with boron carbide particles (5% by wt.) to fabricate Al-B_4C metal matrix composite using stir casting method. After fabrication each experimental specimen was cut as a rectangular block of dimension 51x51x12.7 mm^3. The Al-B_4C composite is mostly used as structural neutron absorber, armor plate materials and as a substrate material for computer hard disks. Due to possession of higher hardness and reinforcement strength Al-B_4C composite materials are difficult to be machined by traditional techniques. There can be many non-conventional machining processes which can be used to machine these kinds of composite materials but Electric Discharge Machining (EDM) is most suitable method to machine Al-B_4C composite in terms of power consumption cost and better material removal rate. Experiments were conducted using the SPARKONIK SN 35 (die sinking type) EDM, with servo control system. The polarity of the electrode was set as negative while that of workpiece was positive. Copper, graphite and EN-19 (tool steel) were used as electrode material and EDM oil (grade LL21) as dielectric fluid. The shape of the electrodes are cylindrical and each having a diameter of 30 mm.

The comprehensive study of the literature survey has revealed that very little research has been done to obtain the optimal levels of EDM process parameters for best outcome in terms of MRR, EWR and SR during machining of Al-B_4C composite.

During a process, material removal rate (MRR) is considered as productivity estimate and our aim is to maximize it while simultaneously minimizing electrode wear rate (EWR) and surface roughness (SR). Maximizing MRR and simultaneously minimizing EWR and SR are the objectives which are opposite in nature. These opposite in nature objectives can be optimized simultaneously by selecting an optimal process parameters. The effect of input parameters of EDM process i.e. current, pulse on time, pulse off time and different electrode material (copper, EN-19 and graphite) on response parameters like MRR, EWR and SR were studied and investigated. Taguchi analysis was carried out to get the optimum levels of input process parameters i.e. current, pulse on time, pulse off time and electrode material to maximize MRR and minimize EWR and SR. For four parameters with three levels, L_9 orthogonal array was used to conduct the experiments. The experimental results were also analyzed using analysis of variance (ANOVA), for identifying the significant input parameters. Based on the results of ANOVA analysis it was found that current and pulse on time are most significant factors affecting material removal rate and surface roughness respectively. It was also found that electrode material and current are most significant parameter for electrode wear rate. To obtain maximum MRR during machining of Al-B_4C composite optimized level of input parameters is A3B1C3D3, i.e. 6 amps current, 6μs pulse on time, 6μs pulse off time with graphite electrode. To obtain minimum EWR during machining optimized level of input parameters is A1B2C2D1 i.e. 2 amps current, 8μs pulse on time, 4μs pulse off time with copper electrode. To obtain lowest SR during machining optimized level of input parameters is A1B3C3D3 i.e. 2 amps current, 10μs pulse on time, 6μs pulse off time with graphite electrode.

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Chapter 1
Introduction to Electric Discharge Machining

1.1 History of EDM

EDM machining techniques were discovered far back in the 1770s by an English Scientist Joseph Priestley. When it was originally observed by Joseph Priestly, EDM machining was very imprecise and riddled with failures. In 1943, soviet scientists B. Lazarenko and N. Lazarenko had exploited the destructive effect of an electrical discharge and developed a controlled process for machining materials that are conductors of electricity.

With the technological and industrial growth, devolvement of hard to machine materials takes place, which have lots of applications in nuclear plants, missile technology, aerospace and space research equipment and other industries due to their high strength to weight ratio, heat resistance and hardness qualities. Figure 1, shows the gradual increase in strength of material with year wise development of material in aerospace industry.

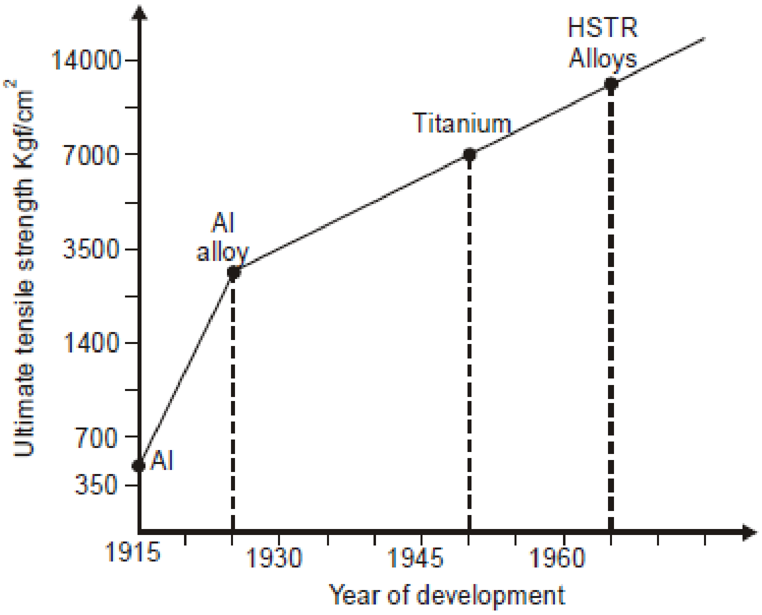

Figure 1- Trend of increase of material strength [1]

Conventional machining processes normally utilize the energy from electric motors, hydraulics and gravity, etc. and depend on the physical contact between tool and workpiece. Hence machining these newer hard materials with conventional machining processes has become uneconomical and unviable. The non-conventional machining on the other hand uses energy from sources such as electrochemical reactions, high temperature plasma, high velocity jets and loose abrasives mixed in various carriers etc. So the non-conventional machining processes are used to machine these newer hard materials and are capable of producing complex shapes, with good quality and surface finish. Currently, non-conventional processes have unlimited process capabilities except for volumetric material removal rates. As material removal rate increases, the cost effectiveness of non-conventional processes also increase, which encourage greater use of these processes.

1.2 Comparative analysis of non-conventional manufacturing processes

A comparative analysis of the different non-conventional manufacturing processes should be made so that a guide-line may be drawn to find the suitability of application of different machining processes.

A particular manufacturing process may be suitable under the given conditions and may not be equally efficient under other conditions. Therefore, a careful selection of the manufacturing process for a given manufacturing problem is essential. The analysis has been made from following point of view:

1.2.1 Physical parameters involved in manufacturing processes

The physical parameters of non-conventional machining processes have a direct effect on the metal removal as well as on the energy consumed in different processes as given in Table-1. The comparative study of the effect of metal removal rate on the power consumed by various non-conventional machining processes is shown in Figure 2.

Processes which lie above the mean power consumption line consume a larger amount of power than the processes lying below the mean power consumption line. Thus, the capital cost involved in the processes lying above the mean line is high whereas for the processes below that line is comparatively low.

From Figure 2, it can be seen that processes like EBM, ECM, AJM and USM lies above while processes like EDM, PAM, ECG and LBM lies below the mean power consumption line. Hence capital cost involved in the processes like EBM, ECM, AJM and USM is comparatively high as compared to the processes like EDM, PAM, ECG and LBM.

1.2.2 Capability of machining different shapes of work piece

The capability of different manufacturing processes can be analyzed on the basis of different machining operation such as micro-drilling, drilling, pocketing etc. as given in Table-2.

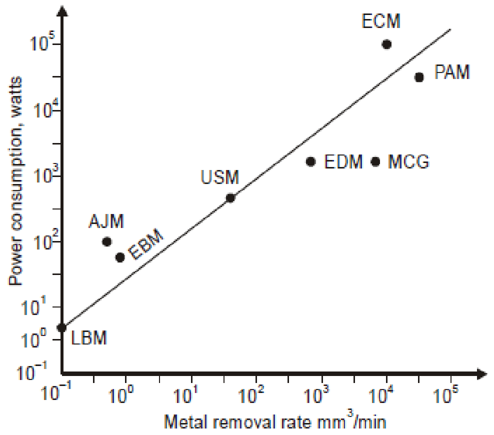

Figure 2- Effect of metal removal rate on power consumption [1]

Table 1 - Physical parameters of the non-conventional processes [1]

Parameters	**USM**	**AJM**	**ECM**	**CHM**	**EDM**	**EBM**	**LBM**	**PAM**
Potential (V)	220	220	10	-	45	150000	4500	100
Current (Amp)	12 (A.C.)	1.0	10000 (D.C.)	-	50 (Pulsed D.C)	0.001 (Pulsed D.C.)	2 (Average 200peak)	500 (D.C.)
Power (W)	2400	220	100000	-	2700	150	-	50000
Gap (mm)	0.25	0.75	0.20	-	0.025	100	150	7.5
Medium	Abrasive in Water	Abrasive in Gas	Electrolyte	Liquid Chemical	Liquid Dielectric	Vacuum	Air	Argon or Hydrogen

For micro-drilling operation, laser beam machining is the only process which has good capability to micro drill while for drilling holes having slenderness ratio, $l/D < 20$, the process USM, ECM and EDM will be most suitable.EDM and ECM processes have good capability to make pocketing operation (shallower deep).ECM process is most suitable for making surface contouring but other processes except EDM have no application for surface contouring operation.

1.2.3 Applicability of processes to various types of material

Materials applications of the different machining methods are given in the Table-3 and Table-4. From these tables it can be seen that ECM and EDM are unsuitable for the machining of electrically non-conducting materials, while mechanical methods used in non-conventional machining can be used to machine electrically non- conductive material. USM is finding suitable for machining of refractory type of material while AJM is suitable for super alloys and refractory materials.

Table 2 - Shape application of non-conventional processes [1]

	Holes				**Through Cavities**		**Surfacing**		**Through Cutting**	
Process	**Precision small holes**		**Standard**		**Precision**	**Standard**	**Double Contouring**	**Surface of Revolution**	**Shallow**	**Deep**
	Dia< .025	**Dia> .025**	**Length <20mm**	**Length >20mm**						
USM	-	-	good	poor	good	good	poor	-	poor	-
AJM	-	-	fair	poor	poor	fair	-	-	good	-
ECM	-	-	good	good	fair	good	good	fair	good	good
CHM	fair	fair	-	-	poor	fair	-	-	good	-
EDM	-	-	good	fair	good	good	fair	-	poor	-
LBM	good	good	fair	poor	poor	poor	-	-	good	fair
PAM	-	-	fair	-	poor	poor	-	poor	good	good

1.2.4 Machining Characteristics

The machining characteristics of different non-conventional machining processes can be analyzed on the basis of following factors and given in Table-5:

a) Metal removal rate

b) Tolerance maintained

c) Surface finish obtained

d) Depth of surface damage

e) Power required for machining

Table 3 - Materials applications of the different machining methods for metal alloys [1]

			Metal Alloys		
Process	**Aluminum**	**Steel**	**Super Alloys**	**Titanium**	**Refractory Material**
USM	poor	fair	poor	fair	good
AJM	fair	fair	good	fair	good
ECM	fair	good	good	fair	fair
CHM	good	-	fair	fair	poor
EDM	fair	good	good	good	good
EBM	fair	fair	fair	fair	good
LBM	fair	fair	fair	fair	poor
PAM	good	good	good	fair	poor

Table 4 - Materials applications of the different machining methods for non-Metals [1]

	Non-Metals		
Process	**Ceramics**	**Plastics**	**Glass**
USM	good	fair	good
AJM	good	fair	good
ECM	-	-	-
CHM	poor	poor	fair
EDM	-	-	-
EBM	good	fair	fair
LBM	good	fair	fair
PAM	-	poor	-

Table 5 - Process capability of different non-conventional manufacturing processes [1]

Process	**MRR (mm^3/min)**	**Tolerance (μ)**	**Surface CLA**	**Depth of Surface Damage**	**Power (Watts)**
USM	300	7.5	0.2-0.5	25	2400
AJM	0.8	50	0.5-1.2	2.5	250
ECM	15000	50	0.1-2.5	5.0	100000
CHM	15	50	0.5-2.5	50	-
EDM	800	15	0.2-1.2	125	2700
EBM	1.6	25	0.5-2.5	250	150 (average) 2000 (peak)
LBM	0.1	25	0.5-1.2	125	2 (average)
PAM	75000	125	Rough	500	50000
Conventional Machining	50000	50	0.-5.0	25	3000

1.2.5 Economics of the processes

The economics of the various processes are analyzed with respect to following factors and shown in Table-6.

a) Capital cost
b) Tooling cost
c) Consumed power cost
d) Metal removal rate efficiency
e) Tool wear.

From Table-6, it was found that the capital cost of ECM is very high when compared with conventional mechanical contour grinding and other non-conventional machining processes while capital costs involved for AJM and PAM are comparatively low. For EDM tooling cost is higher than other machining processes. For PAM and LBM processes power consumption is very low while power consumption is much larger for ECM. The metal removal efficiency is very high for EBM and LBM than for other processes.

Table 6 - Economics of the various processes [1]

Process	**Capital cost**	**Tooling cost**	**Power consumption cost**	**Material removal rate efficiency**	**Tool wear**
USM	L	L	L	H	M
AJM	VL	L	L	H	L
ECM	VH	M	M	L	VL
CHM	M	L	H (cost of Chemical)	M	VL
EDM	M	H	L	H	H
EBM	H	L	L	VH	VL
LBM	L	L	VL	VH	VL
PAM	VL	L	VL	VL	VL

In conclusion, the suitability of application of any of the processes is dependent upon various factors and must be considered all or some of them before applying any non-conventional process.

Being the most versatile among all the non- conventional machining Electrical Discharge Machining (EDM) process is widely used for making tools, dies and other precision parts as it is capable of machining geometrically complex or hard material components made of heat treated tool steels, composites, super alloys, ceramics, carbides, heat resistant steels etc.

The EDM process can be compared with the conventional machining processes like milling and turning as shown in Table-7.

Table 7 - EDM Compared to Conventional Machining [1]

Characteristics	**Conventional Machining (Milling/Drilling)**	**EDM**
Contact between workpiece and cutting tool	Yes	No
Force	Yes	No
Tool/ Workpiece Rotation	Yes	Not Normally
Tool/ Workpiece Conductive	Not Required	Yes
Material Removal Method	Shear	Melt/ Vaporize

1.3 Introduction of EDM

Electrical Discharge Machining (EDM) is a thermal erosion process used to remove material by a number of repetitive electrical discharges of small duration and high current density between the workpiece and the tool as shown in Figure 3.

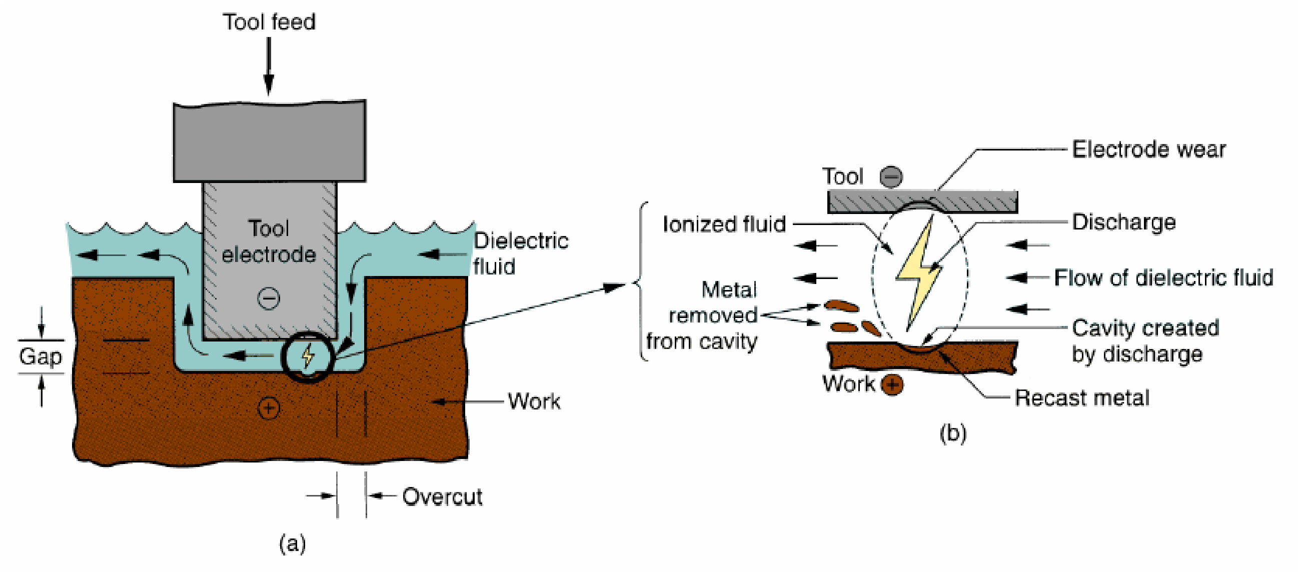

Figure 3-EDM process showing discharge and metal removal [2]

EDM is mainly used to machine high strength temperature resistant alloys and materials which are difficult-to-machine. EDM can be used to machine irregular geometries in small batches or even on job-shop basis. In EDM, as there is no direct contact between the workpiece and the electrode, hence there are no mechanical forces existing between workpiece and electrode but work material must be electrically conductive to be machined by EDM.

1.4 Principle of EDM

In EDM, a potential difference is applied between the tool and workpiece. Both the tool and the work material must be conductors of electricity. Both work piece and tool are submerged in a dielectric fluid commonly used are EDM oil, kerosene and deionized water. A constant gap is maintained between the tool and the workpiece with the help of Servo control as shown in Figure 4.

Depending upon the applied potential difference and the gap between the tool and workpiece, an electric field would be generated. Generally the work piece is made anode and tool is made cathode. As the electric field is established between the tool and the workpiece, the free electrons on the tool are subjected to electrostatic forces. If the work function or the bonding energy of the electrons is small, electrons would be emitted from the tool (assuming it to be connected to the negative terminal). Such emissions of electrons are called as cold emission.

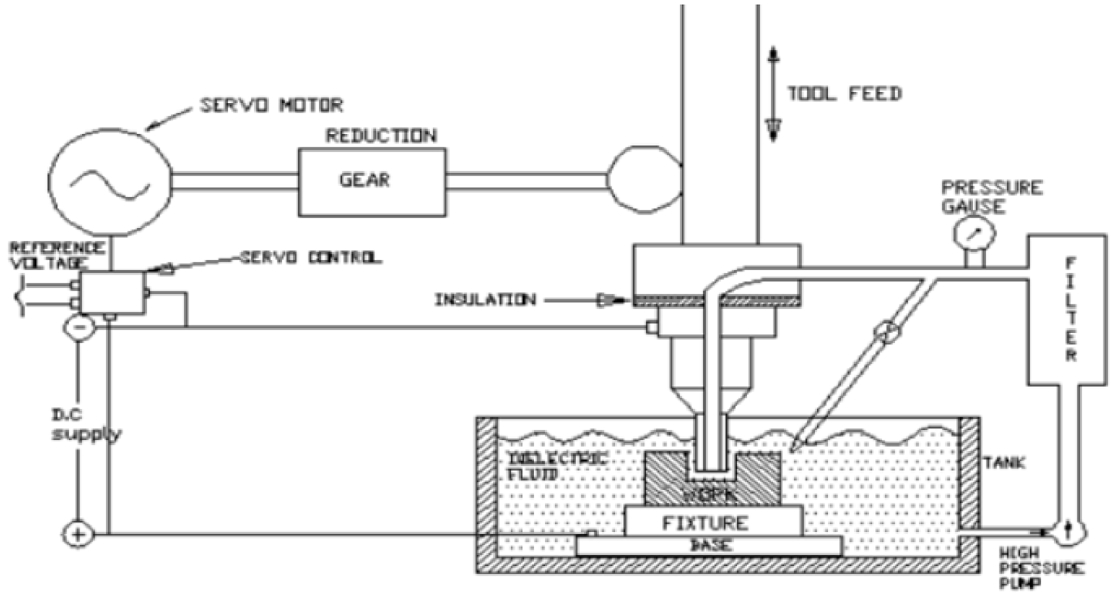

Figure 4- Electric Discharge Machining set up [3]

The “cold emitted” electrons are then accelerated towards the job through the dielectric medium. As they gain velocity and energy, and start moving towards the job, there would be collisions between the electrons and dielectric molecules. Such collision may result in ionization of the dielectric molecule depending upon the work function or ionization energy of the dielectric molecule and the energy of the electron. Thus, as the electrons get accelerated, more positive ions and electrons would get generated due to collisions. This cyclic process would increase the concentration of electrons and ions in the dielectric medium between the tool and the job at the spark gap. The concentration would be so high that the matter existing in that channel could be characterized as “plasma”. The electrical resistance of such plasma channel would be very less. Thus all of a sudden, a large number of electrons will flow from the tool to the job and ions from the job to the tool. This is called avalanche motion of electrons. Such movement of electrons and ions can be visually seen as a spark as shown in Figure 5. Thus the electrical energy is dissipated as the thermal energy of the spark.

The high speed electrons then impinge on the job and ions on the tool. The kinetic energy of the electrons and ions on impact with the surface of the job and tool respectively would be converted into thermal energy or heat flux. Such intense localized heat flux leads to extreme instantaneous confined rise in temperature which would be in excess of 10,000^{o}C.

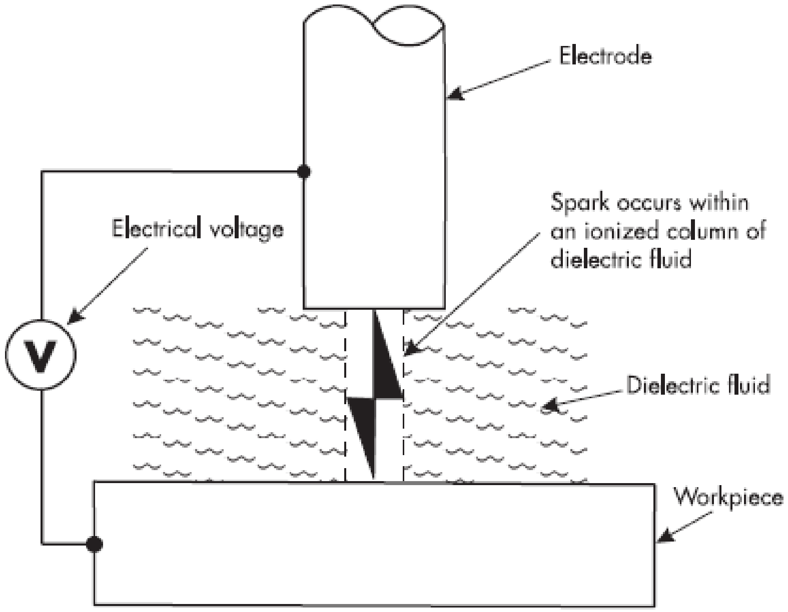

Figure 5- Spark occurs within a column of ionized dielectric fluid [4]

Due to such localized extreme rise in temperature a small amount of the electrode and workpiece material is vaporized. The vaporized material is positioned in the sparking gap between the electrode and workpiece which is known as a cloud. As the potential difference is withdrawn as shown in Figure 6 the plasma channel is no longer sustained and the spark is turned off, due to which the vaporized cloud solidifies.

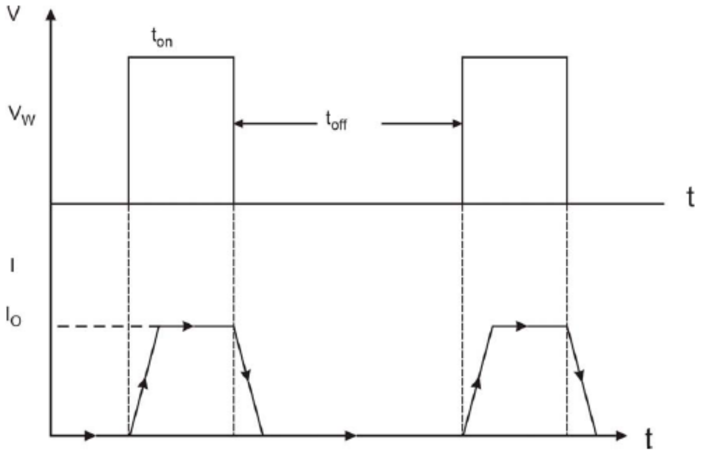

Figure 6 - Waveforms used in EDM
V_w-Working voltage, I_o- Maximum current

Each spark then produces an EDM chip or a very tiny hollow sphere of material made up of the electrode and workpiece material. For efficient machining, the EDM chip must be removed from the sparking area. Removal of this chip is accomplished by flowing dielectric fluid through the sparking gap. Figures 7, 8 and 9 illustrate the spark producing the vapor cloud, the cloud in suspension, and the vaporized cloud being cooled and forming into an EDM chip.

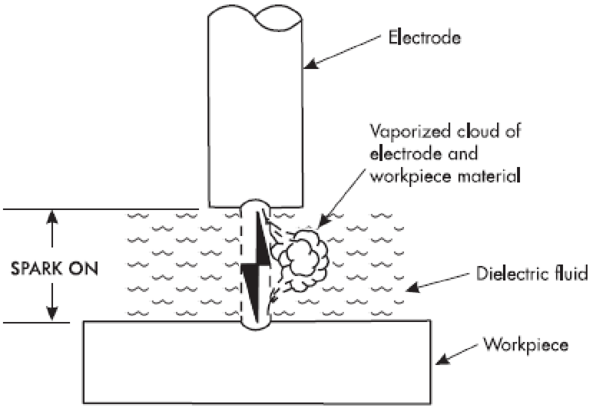

Figure 7 - Spark ON: Electrode and workpiece material vaporized [4]

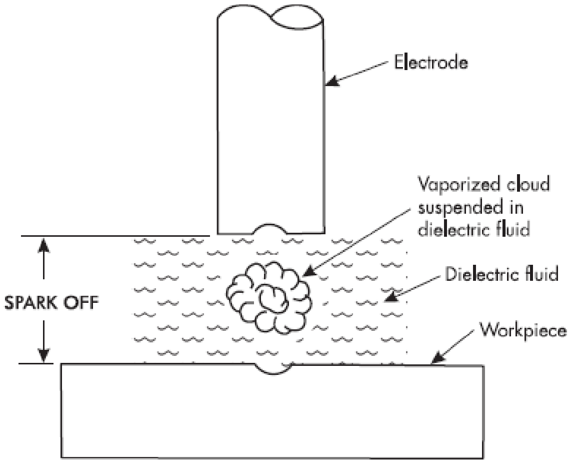

Figure 8 - Spark OFF: Vaporized cloud suspended in dielectric fluid [4]

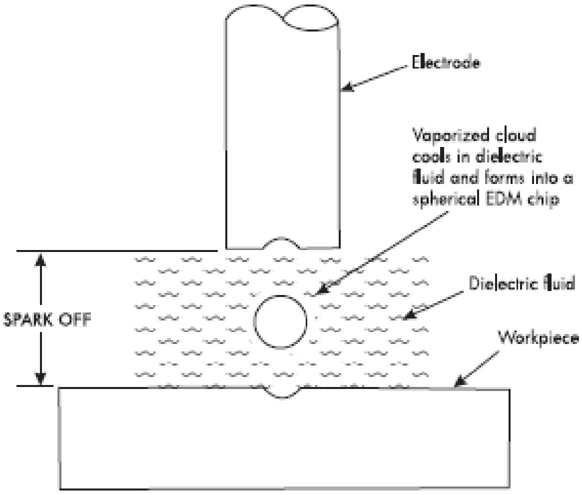

Figure 9 - Spark-OFF: Vaporized cloud solidifies to form EDM chip [4]

In EDM, the generator is used to apply voltage pulses between the tool and the workpiece as shown in Figure 6. A constant voltage is not applied as only sparking is desired in EDM not arcing. Arcing results in localized material removal at a particular point while sparks get distributed all over the tool surface which results in uniformly distributed material removal under the tool. In EDM, the sparks move from one point on the electrode to another as sparking takes place. Figure 10 and 11 shows that each spark occurs between the closest points of the electrode and the workpiece.

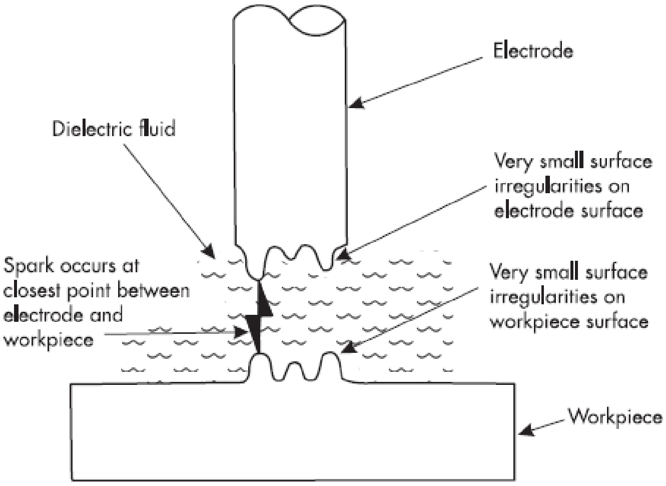

Figure 10 - Sparking occurs at closest points between electrode & workpiece [4]

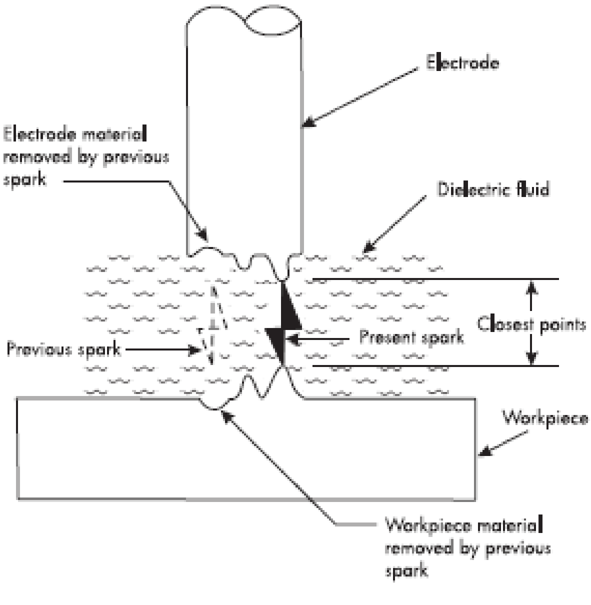

Figure 11 - Next spark occurs at closest points between electrode & workpiece [4]

Thus to summaries, the material removal in EDM mainly occurs due to formation of shock waves as the plasma channel collapse owing to discontinuation of applied potential difference.

1.5 Types of EDM process

Basically, there are two types of EDM:

1.5.1 Die Sinking EDM

Die-sinking EDM is also known as Volume EDM or cavity type EDM. During the EDM process the workpiece and the electrode are submerged in the dielectric oil, which is an electrical insulator that helps to control the arc discharge. The dielectric oil, that provides a means of flushing, is pumped through the arc gap. This removes suspended particles of workpiece material and electrode from the work cavity.

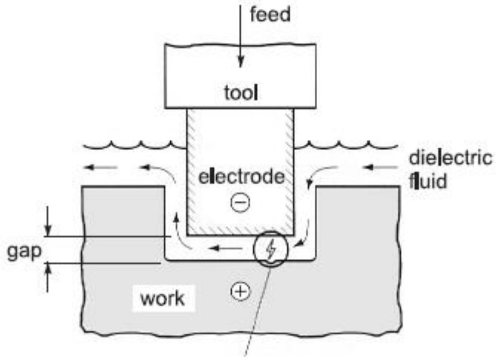

Figure 12 - Die sinking EDM process [5]

1.5.2 Wire Cut EDM

Wire-cut EDM, also known as Spark EDM .The wire-cut EDM is a discharge machine that uses CNC movement to produce the desired contour or shape. It does not require a special shaped electrode; instead it uses a continuous-traveling vertical wire under tension as the electrode. The electrode in wire-cut EDM is about as thick as a small diameter needle whose path is controlled by the machine computer to produce the shape required.

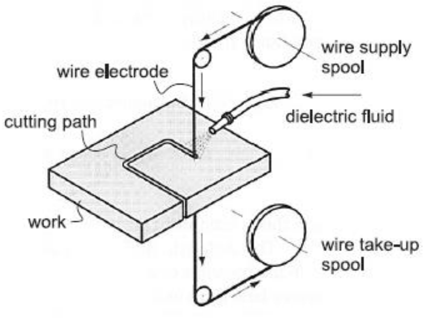

Figure 13 - Wire cut EDM process [5]

1.6 Important parameters of EDM

1.6.1 Pulse on-time (T_{on})

The pulse on-time shows the duration of time in micro seconds (μs) during which the voltage pulse is applied in each cycle as shown in Figure 6. Amount of Material removed is directly proportional to the amount of energy applied during this pulse on-time. This energy is controlled by the peak current and the length of the pulse on-time. With increase in pulse on time the pulse discharge energy increases which increases the machining rate. But use of higher values of Ton, will also increase surface roughness.

1.6.2 Pulse off Time (T_{off})

The pulse off-time shows the duration of time in micro seconds (μs), between the two consecutive sparks as shown in Figure 6. This time allows the molten material to solidify and to be wash out of the arc gap. During this part of the cycle the voltage is not present. If a lower value of pulse off time is used there will be more number of discharges in a given time, due to which sparking efficiency increases which improves cutting efficiency. But if the off-time is too short, the spark will unstable. This parameter affects the speed and the stability of the cut.

1.6.3 Arc gap

The arc gap is distance between the electrode and workpiece during the process of EDM. It may be called as spark gap.

1.6.4 Discharge current (I)

The discharge current is the maximum value of the current passing through the electrodes for a given pulse. Increase in the discharge current will increase the dischargeenergy due to which material removal rate increases.

1.6.5 Duty cycle (τ)

It is a percentage of the on-time relative to the total cycle time. This parameter is calculated by dividing the on-time by the total cycle time.

$$\tau = \frac{Ton}{Ton + Toff} \tag{1}$$

1.6.6 Voltage (V)

It is the potential difference applied between the electrode and the workpiece. It also affects the material removal rate.

1.6.7 Over cut

It is a clearance per side between the electrode and the workpiece after the machining operation.

1.6.8 Flushing

One of the most important factors in a successful EDM operation is the removal of the metal particles (chips) from the working gap. Flushing these particles out of the gap between the workpiece to prevent them from forming bridges that cause short circuits.

1.6.9 Servo mechanism

Die sink EDM machines are equipped with a servo control mechanism that automatically maintains a constant gap of about the thickness of a human hair between the electrode and the workpiece. It is important that there is no physical contact between the electrode and the workpiece, otherwise arcing could damage both the workpiece and electrode. The servomechanism advances the electrode into the workpiece as the operation progresses and senses the work-electrode spacing and controls it to maintain the proper arc gap which is essential to a successful machining operation.

1.7 Application of EDM

i) The EDM process is becoming a common method of making prototype and production parts, especially in the aerospace, automobile and electronics industries in which production quantities are relatively low.
ii) It is used to machine extremely hard materials that are difficult to machine like alloys, tool steels, tungsten carbides, composites ceramics etc.
iii) It is used for drilling of curved holes.
iv) It is used for internal thread cutting and helical gear cutting.
v) It is used for machining sharp edges and corners that cannot be machined effectively by other machining processes.
vi) In EDM machining higher Tolerance limits can be obtained. Hence areas that require higher surface accuracy use the EDM machining process.
vii) It is a promising technique to meet increasing demands for smaller components usually highly complicated, multi-functional parts used in the field of micro-electronics.

1.8 Advantages of EDM

i) Any material that is electrically conductive can be cut using the EDM process.

ii) Hardened workpieces can be machined and the deformation caused by heat treatment is eliminated.

iii) X, Y and Z axes movements allow for the programming of complex profiles using simple electrode.

iv) Complex dies sections and molds can be produced accurately, faster, and at lower costs.

v) Thin fragile sections such as webs or fins can be easily machined without deforming the part.

1.9 Limitations

i) The work piece has to be electrically conductive to be able to create discharges. Isolators like plastics, glass and most ceramics cannot be machined by EDM. Machining of partial conductors like Si semi-conductors, partially conductive ceramics and even glass is also possible.

ii) The material removal of the EDM-process is low, especially in the case of die-sinking EDM where the total volume of a cavity has to be removed by melting and evaporating the metal. Due to the low material removal rate, EDM is principally limited to the production of small series although some specific mass production applications are known.

iii) Beneath the recast layer is a heat affected zone which may be softer than parent material.

iv) Dielectric vapour can be dangerous

v) Slightly tapered holes, especially if blind.

1.10 Disadvantages of EDM

i) The wear rate on the electrode is considerably higher. Sometimes it may be necessary to use more than one electrode to finish the job.

ii) The workpiece should be electrically conductive to be machined using the EDM process.

iii) The energy required for the operation is more than that of the conventional process and hence will be more expensive.

Chapter 2

Literature Survey

2.1 Introduction

In this chapter research papers are selected, related to EDM which affects the workpiece material removal rate, electrode wear rate and surface roughness of workpiece material. All the papers are classified in to three different categories, i.e., papers related to workpiece and tool material, papers related to different tool shapes and size and papers related to fabrication of MMC.

2.1.1 Research papers related to workpiece and tool material

P.Narender et al. [6] investigated the relationship of process parameters in EDM of Al-10%SiCp as workpiece and Brass as tool material. The author investigate the effect of Current, pulse on time and flushing pressure on material removal rate (MRR), tool wear rate (TWR), taper (T), radial overcut (ROC) and surface roughness (SR) on machining of Al MMC with 10% SiCp reinforcement. It was found that MRR is higher for larger current and pulse on time at the expense of taper-city, radial overcut and surface finish; whereas at higher current settings TWR is also higher. It was also find that flushing pressure of the dielectric has considerable effect on the MRR and TWR.

S.H.Tomadi et al. [7] investigated the relationship of process parameters in EDM of Tungsten Carbide selected as workpiece and Copper Tungsten as an electrode. Pulse on time, Pulse off time, Supply Voltage and peak current are considered as input process parameters and the material removed rate (MRR) and electrode wear rate (EWR) are considered as process performances. The full factorial design of experiment was used to analysis the optimum condition of machining parameters. Author concluded that for surface roughness the most influential factor were voltage followed by pulse off time, peak current and in case of material removal rate, it was seen that the pulse on time factor was the most influential, followed by voltage, peak current and pulse off time.

Mohd. AmriLajis et al. [8] investigated the relationship of process parameters in EDM of Tungsten Carbide selected as workpiece and Graphite as an electrode. Peak current, pulse off time, pulse on time and current are considered as input process parameters and the metal removal Rate (MRR), electrode wear rate (EWR) and surface roughness (SR) are considered as process performances. Taguchi methodology has been used to formulate the experimental layout, to analyze the effect of each parameter on the machining characteristics, and to predict the optimal EDM parameters. It was concluded that, the peak current of EDM mainly affects the electrode wear and surface roughness and the pulse on time largely affects the metal removal rate.

A.Majumder et al. [9] derived quadratic mathematical model to represent the process behavior of Die-Sinking Electrical Discharge Machining. Experiments has been conducted with three process parameters viz. discharge current, pulse on time and pulse off time and to relate them with process responses viz. material removal rate (MRR) and electrode wear rate (EWR). Experiment was performed with mild steel as workpiece and copper as electrode and finding that the effect of supply current on material removal rate is higher than the other machining parameters while in case of electrode wear rate (EWR) the most influential factor was the intensity of the pulse-on time.

S. Gopalakannan et al. [10] investigated the influence of process parameters and their interactions viz., pulse current, gap voltage, pulse on time and pulse off time on MRR, EWR and SR. experiments were carried out to machine newly engineered metal matrix composite of aluminum 7075 reinforced with 10% of B_4C particles using copper as electrode. Response Surface Methodology had been employed to develop mathematical model and to establish empirical relationships between process parameters and process responses. Analysis of variance was carried out to validate the experimental results. It was concluded that the two main significant factors that affects the MRR are pulse current and pulse on time. The MRR first increases and then decreases with increasing pulse on time. The surface roughness increases with increase in pulse current and pulse on time & surface roughness decreases upto 50 volt and then increases with further increase in voltage.

Raj Mohan et al. [11] investigated the influence of process parameters and their interactions viz., voltage, pulse on time, current and pulse off time on the material removal rate (MRR) in stainless steel (304) as workpiece. Signal to noise ratio (S/N) and analysis of variance (ANOVA) was used to analyze the effect of the parameters on MRR and Taguchi method used to find the optimum cutting parameters. It was concluded that the two main significant factors that affects the MRR are pulse current and pulse on time.

Nikalje et al. [12] studied the influence of process parameters such as discharge current, pulse-on-time and pulse-off-time for process performance criteria such as MRR, Tool Wear Ratio (TWR), Relative Wear Ratio (RWR) and surface roughness. The MDN 300 steel was used as workpiece material and copper as electrode. The Taguchi method was employed for optimization. It was found that the optimal levels of the factors for SR and TWR are same but differs from the optimum levels of the factors for MRR and RWR. From ANOVA, discharge current is more significant than pulse on time for MRR and TWR; whereas pulse on time is more significant than discharge current for RWR and SR. on the other hand, pulse off time is less significant for all performance characteristics considered.

Nilesh M. Vohra et al. [13] investigated the optimum cutting parameters for a work piece (SS-304) & tool material (Copper, Aluminum, Brass) combination on Fuzzy Logic Control based Electrical Discharge Machine to find out the effect of process parameters viz. tool material, current, spark gap voltage, pulse on time and pulse off time on material removal rate (MRR), tool wear ratio (TWR), surface roughness (SR). It was found that gap voltage is more significant for MRR and SR But tool material is more significant for TWR.

Chandramouli S et al. [14] investigated the relationship of process parameters in EDM of RENE80 Nickel Super Alloy as workpiece and aluminum as an electrode. Current, pulse on time, pulse off time are used as input process parameters and the MRR, TWR and SR are considered as a process performances. It was found that MRR is increasing with increase in current, pulse on time and pulse off time but increase is less as compared to the pulse on time; whereas TWR is increasing with increase in current and pulse off time while decreases with increase in pulse on time. It was also found that SR is increasing with increase in current and pulse on time but decreasing with increase in pulse off time.

S. Suresh Kumar et al. [15] found that during electric discharge machining of Al (6351)-SiC-B_4C hybrid composite, increase in pulse current increases the electrode wear ratio and the surface roughness. However, pulse on time and the pulse duty factor have a negative influence on electrode wear ratio. It was also found that lower the pulse duration and pulse duty factor better will be the surface finish, but pulse duty factor doesn't contributes significantly. Power consumed during machining was reduced with an increase in pulse current and pulse duty factor. However, the pulse duration has to be low to minimize the machining cost.

2.1.2 Research papers related to tool Shapes and Size

Sohani et al. [16] presented the application of response surface methodology (RSM) for investigating the effect of tool shapes such as triangular, square, rectangular and circular with size factor consideration along with other process parameters like discharge current, pulse on time, pulse off time and tool area. The investigation revealed that the best tool shape for higher MRR and lower TWR is circular, followed by triangular, rectangular and square cross-sections. From the parametric analysis, it was also observed that the interaction effect of discharge current and pulse on time is highly significant on MRR and TWR, whereas the main factors such as pulse off time and tool area are statistically significant on MRR and TWR. The ANOVA was employed along with Fisher's test (F- test) at 95% confidence interval to verify the lack of fit and adequacy of developed model.

Ashok Kumar et al.[17] investigated the effect of process parameters like Pulse on time, Discharge current and Diameter of electrode on material removal rate (MRR), Tool wear rate (TWR) and over cut. The experiment used AISI P20 tool steel as workpiece and U-shaped copper tool as electrode with internal flushing system. The S/N ratios used for minimizing the TWR and maximizing the MRR and Taguchi method used for optimization the process parameters. It was concluded that pulse on time was the most influencing factor for MRR and then discharge current and the last one is the diameter of the tool. MRR increased with the discharge current and in case of the tool wear rate, the most influencing factor is pulse on time then discharge current and after that diameter of tool.

2.1.3 Research papers related to fabrication of metal matrix composites

S. Rama Rao et al. [18] investigated the fabrication and mechanical properties of aluminum-boron carbide composites. In this context aluminum alloy - boron carbide composites were fabricated by liquid metallurgy techniques with different particulate weight fraction (2.5, 5 and 7.5%). It was found that with the increase of the amount of the boron carbide, the density of the composites decreased whereas the hardness is increased. The ultimate compressive strength of the composites was increased with increase in the weight percentage of the boron carbide in the composites.

Amol D. Sable et al. [19] investigated preparation of metal-matrix composites by stir-casting method this paper emphasize the production of metal-matrix Al-SiC composites using the stir-casting method and prepared total six samples of varying percentile compositions of SiCp – 5%, 10%, 15%, 20%, 25% and 30% with aluminium. The main purpose this paper is to develop the strong light weighted metal-matrix Al-SiC composite material at low cost which is useful in the industrial sectors as well as advanced machineries.

2.2 Research gap

After a comprehensive study of the existing literature survey, it reveals that large amount of research work has been carried out in the area of metal matrix composites. Aluminum matrix composites have an advantage among MMCs, as aluminum is of light weight, high strength and easy to fabricate. But limited work has done on the machining of Al-B_4C MMCs using EDM. Most of the researchers have investigated influence of input parameters like current, pulse on time, pulse off time, flushing pressure and gap voltage etc. during machining of Al-B_4C composite, but the effect of different tool materials on process performances viz. material removed rate (MRR), electrode wear rate (EWR) and surface roughness (SR) has not been investigated yet.

2.3 Objective of the present work

Based on the literature review of the research work, the objectives of the present research work are:

i) Fabrication of Al 6061 metal matrix composites reinforced with boron carbide particles (5% by wt.) using stir casting process.

ii) Examine the microstructure of the fabricated composite to confirm the uniform distribution of boron carbide particles in the composite.

iii) Investigate the effect of input process parameters like current, pulse on time, pulse off time and different electrode materials on the process performance like MRR, EWR and SR using Taguchi technique to predict optimum levels of input process parameters.

Chapter 3
Experimental Design Methodology

3.1 Introduction

Design of experiments (DOE) or experimental design is the design of any information-gathering exercises where variation is present, whether under the full control of the experimenter or not. However, in statistics, these terms are usually used for controlled. A properly planned and executed experiment is of the utmost importance for deriving clear and accurate conclusions from the experimental observations. Design of experiment is considered to be a very useful strategy for accomplishing these tasks. The science of statistical experimental design originated with the work of Sir Ronald Fisher in England in 1920s. Fisher founded the basic principle of experimental design and the associated data-analysis technique called Analysis of Variance (ANOVA) during his efforts to improve the yield of agricultural crops. The theory and applications of experimental design and the related technique of response surface methodology have been advanced by many statistical researchers as Box and Hunter, Box and Draper, Hicks. Various types of matrices are used for planning experiments to study several decision variables. Among them, Taguchi's Method makes heavy use of orthogonal arrays.

The advantages of design of experiments are as follows:

i) Numbers of trials is significantly reduced.

ii) Important decision variables which control and improve the performance of the product or the process can be identified.

iii) Optimal setting of the parameters can be found out.

iv) Qualitative estimation of parameters can be made.

v) Experimental error can be estimated.

vi) Inference regarding the effect of parameters on the characteristics of the process can be made.

3.2 Taguchi's experimental design and analysis

The Taguchi method involves reducing the variation in a process through robust design of experiments. The overall objective of the method is to produce high quality product at low cost to the manufacturer. The Taguchi method was developed by Dr. Genichi Taguchi of Japan. Taguchi developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varies. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources. The Taguchi method is best used when there are an intermediate number of variables (3 to 50), few interactions between variables, and when only a few variables contribute significantly.

3.3 Philosophy of Taguchi method

Quality should be designed into a product, not inspected into it. Quality is designed into a process through system design, parameter design, and tolerance design. Parameter design, which will be the focus of this article, is performed by determining what process parameters most affect the product and then designing them to give a specified target quality of product. Quality "inspected into" a product means that the product is produced at random quality levels and those too far from the mean are simply thrown out.

Quality is best achieved by minimizing the deviation from a target. The product should be designed so that it is immune to uncontrollable environmental factors. In other words, the signal (product quality) to noise (uncontrollable factors) ratio should be high.

The cost of quality should be measured as a function of deviation from the standard and the losses should be measured system wide. This is the concept of the loss function, or the overall loss incurred upon the customer and society from a product of poor quality. Because the producer is also a member of society and because customer dissatisfaction will discourage future patronage, this cost to customer and society will come back to the producer.

3.4 Taguchi method designs of experiments

The general steps involved in the Taguchi Method are as follows:

i) Define the process objective, or more specifically, a target value for a performance measure of the process. This may be a flow rate, temperature, etc. The target of a process may also be a minimum or maximum; for example, the goal may be to maximize the output flow rate. The deviation in the performance characteristic from the target value is used to define the loss function for the process.

ii) Determine the design parameters affecting the process. Parameters are variables within the process that affect the performance measure such as temperatures, pressures, etc. that can be easily controlled. The number of levels that the parameters should be varied at must be specified. For example, a temperature might be varied to a low and high value of 40^0C and 80^0C. Increasing the number of levels to vary a parameter increases the number of experiments to be conducted.

iii) Create orthogonal arrays for the parameter design indicating the number of and conditions for each experiment. The selection of orthogonal arrays is based on the number of parameters and the levels of variation for each parameter, is explained below.

iv) Conduct the experiments indicated in the completed array to collect data on the effect on the performance measure.

v) Complete data analysis to determine the effect of the different parameters on the performance measure.

3.5 Experimental design strategy

Taguchi recommends orthogonal arrays (OA) for lying out of experiments. These OA's are generalized Graeco-Latin squares. To design an experiment is to select the most suitable OA and to assign the parameters and interactions of interest to the appropriate columns. The use of linear graphs and triangular tables suggested by Taguchi makes the assignment of parameters simple. The array forces all experimenters to design almost identical experiments.

In the Taguchi method the results of the experiments are analyzed to achieve one or more of the following objectives:

- To estimate the best or the optimum condition for a product or process.
- To estimate the contribution of individual parameters and interactions.
- To estimate the response parameters under the optimum condition.

The optimum condition is identified by studying the main effects of each of the parameters. The main effects indicate the general trend of influence of each parameter. The knowledge of contribution of individual parameters is a key in deciding the nature of control to be established on a production process. The analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiments in determining the percent contribution of each parameter against a stated level of confidence. Study of ANOVA table for a given analysis helps to determine which of the parameters need control. Taguchi suggests two different routes to carry out the complete analysis of the experiments. First the standard approach, where the results of a single run or the average of the repetitive runs are processed through main effect and ANOVA analysis (Raw data analysis). The second approach which Taguchi strongly recommends for multiple runs is to use signal-to-noise (S/N) ratio for the same steps in the analysis. The S/N ratio is a concurrent quality metric linked to the loss function. By maximizing the S/N ratio, the loss associated can be minimized. The S/N ratio determines the most robust set of operating conditions from variation within the results. The S/N ratio is treated as a response parameter (transform of raw data) of the experiment. Taguchi recommends the use of outer OA to force the noise variation into the experiment i.e. the noise is intentionally introduced into the experiment. Generally, processes are subjected to many noise factors that in combination strongly influence the variation of the response. For extremely 'noisy' systems, it is not generally necessary to identify controllable parameters and analyze them using an appropriate S/N ratio. In the present investigation, both the analysis: the raw data analysis and S/N data analysis have been performed. The effects of the selected EDM parameters on the selected quality characteristics have been investigated through the main effects plots based on raw data. The optimum condition for each of the quality characteristics have been establish through S/N data analysis. No outer array has been used and instead, experiments have been repeated two times at each experimental condition.

3.6 Loss function and S/N ratio

The heart of Taguchi method is his definition of nebulous and elusive term 'quality' as the characteristic that avoids loss to the society from the time the product is shipped. Loss is measured in terms of monetary units and is related to quantifiable product characteristics. Taguchi defines quality loss via his 'loss-function'. He unites the financial loss with the functional specification through a quadratic relationship that comes from Taylor series expansion.

$$L(y) = k(y - m)^2 \qquad (2)$$

where, L = loss in monetary unit

m = value at which the characteristic should be set

y = actual value of the characteristic

k = constant depending on the magnitude of the characteristic and the monetary unit involved.

The following two observations can be made

i) The further the product's characteristic varies from the target value, the greater is the loss. The loss is zero when the quality characteristic of the product meets its target value.

ii) The loss is a continuous function and not a sudden step as in the case of traditional approach.

This consequence of the continuous loss function illustrates the point that merely making a product within the specification limits does not necessarily mean that product is of good quality.

In a mass production process the average loss per unit is expressed as:

$$L(y) = k\sum(y_i - m)^2 \qquad (3)$$

where i = 1, 2……………n

n = number of units in a given sample

y_i = values of characteristics for units 1, 2,........n

k = constant depending upon the magnitude of characteristic and the monitory unit involve

m= Target value at which characteristic should be set

Equation can be written as:

$$L(y) = k(MSD) \qquad (4)$$

Where MSD denotes mean square deviation, which presents the average squares of all deviations from the target value rather than around the average value

Taguchi transformed the loss function into a concurrent statistic called S/N ratio, which combines both the mean level of the quality characteristic and variance around this mean into a single metric. The S/N ratio consolidates several repetitions (at least two data points are required) into one value. A high value of S/N ratio indicates optimum value of quality with minimum variation. Depending upon the type of response, the following three types of S/N ratio are used in practice.

1. Higher the better (HB) :

$$(S/N)_{HB} = -10\log(MSD)_{HB} \qquad (5)$$

where

$$(MSD)_{HB} = \frac{1}{2}\sum_{j=1}^{R}\left(\frac{12}{yj}\right) \qquad (6)$$

2. Lower the better (LB):

$$(S/N)_{LB} = -10\log(MSD)_{LB} \qquad (7)$$

where

$$(MSD)_{LB} = \frac{1}{R\sum_{\mathrm{j=1}}^{\mathrm{R}}\mathrm{y}_{21}} \qquad (8)$$

3. Nominal the best(NB) :

$$(S/N)_{NB} = -10\log(MSD)_{NB} \qquad (9)$$

Where

$$(MSD)_{NB} = \frac{1}{\mathrm{R}}\sum_{\mathrm{J}=1}^{\mathrm{R}}\left(\mathrm{y_j} - \mathrm{y_0}\right)^2 \qquad (10)$$

R = Number of repetitions

It is to be mentioned that for nominal the best type of characteristic, the standard definition of MSD has been used. For smaller the better type the target value is zero. For larger the better type, the inverse of each large value becomes a small value and again the target value is zero. Therefore, for all the three expressions the smallest magnitude of MSD is being sought. The constant 10 has been purposely used to magnify S/N number for each analysis and negative sign is used to set S/N ratio of larger the better relative to the square deviation of smaller the better.

3.7 Taguchi procedure for experimental design and analysis

The stepwise procedure for Taguchi experimental design and analysis is described in the following paragraphs.

3.7.1 Selection of orthogonal array

In selecting an appropriate OA, the following prerequisites are required:

- Selection of process parameters and/or their interactions to be evaluated.
- Selection of number of levels for the selected parameters.

Several methods are suggested by Taguchi for determining which parameters to include in an experiment. These are:

- Brainstorming
- Flow charting
- Cause-effect diagram

Thus, two levels for each parameter are recommended to minimize the size of the experiment. If curved or higher order polynomial relationship between the parameters under study and the response is expected, at least three levels for each parameter should be considered. The standard two-level and three-level arrays are:

a) Two-level arrays: L_4, L_8, L_{12}, L_{16}, L_{32}

b) Three-level arrays: L_9, L_{18}, L_{27}

The number as subscript in the array designation indicates the number of trials in that array. The degree of freedom (DOF) available in an OA is:

$$f_{LN} = (N - 1) \tag{11}$$

Where

f_{LN} = total degrees of freedom of an orthogonal array
L_N=Orthogonal array designation
N = number of trials

When a particular orthogonal array is selected for an experiment, the following inequality must be satisfied:

$$f_{LN} \geq Total\ DOF\ required\ for\ parameters\ and\ interaction \tag{12}$$

Depending on the number of levels in the parameters and total DOF required for the experiment, a suitable orthogonal array is selected.

3.7.2 Assignment of parameters and interactions to orthogonal array

An orthogonal array has several columns to which various parameters and their interactions are assigned. Linear graphs and Triangular tables are two tools, which are useful for deciding the possible interactions between the parameters and their assignment in the columns of orthogonal array. Each orthogonal array has its particular liner graphs and interaction tables

3.7.3 Selection of outer array

Taguchi separates factors (parameters) into two main groups:

- Controllable factors
- Noise factors

Controllable factors are factors that can easily be controlled. Noise factors, on the other hand, are nuisance variables that are difficult, impossible, or expensive to control. The noise factors are responsible for the performance variation of a process. Taguchi recommends the use of outer array for noise factors and inner array for the controllable factors. If an outer array is used the noise variation is forced into the experiment. However, experiments against the trial condition of the inner array may be repeated and in this case the noise variation is unforced in the experiment. The outer array, if used will have the same assignment considerations.

3.7.4 Experimentation and data collection

The experiment is performed against each of the trial conditions of the inner array. Each experiment at a trial condition is repeated simply (if outer array is not used) or according to the outer array (if used). Randomization should be carried for to reduce bias in the experiment.

3.7.5 Data analysis

A number of methods have been suggested by Taguchi for analyzing the data: observation method, ranking method, column effect method, ANOVA, S/N ANOVA, plot of average responses, interaction graphs, etc. In the present work, following methods are used.

- Response table for S/N Ratios
- Main Effect Plot for Means
- Main Effect Plot for S/N Ratios
- ANOVA for S/N Data

The plot of average responses at each level of a parameter indicates the trend. It is a pictorial representation of the effect of a parameter on the response. The S/N ratio is treated as a response of the experiment, which is a measure of the variation within a trial when noise factors are present. A standard ANOVA is conducted on raw data, which identified the significant parameters.

Chapter-4

Experimentation, Instrumentation and Material Selection

In this chapter the experimental work prior to machining operation was formulated. It consists of selection of workpiece material, fabrication of Al 6061 metal matrix composite reinforced with B_4C particles, microstructure study of the fabricated composite, experimental set-up, tool design and calculation of material removal rate, electrode wear rate and surface roughness.

4.1 Experimental set- up

The experiments were conducted using the SPARKONIK SN 35 (die sinking type) Electric Discharge Machine, with servo control system as shown in Figure 14.The machine has 6 current settings between 1A to 10A, 9 settings of pulse off time and 9 setting of pulse on time. The polarity of the electrode was set as negative while that of workpiece was positive. The dielectric fluid used was EDM oil LL21.

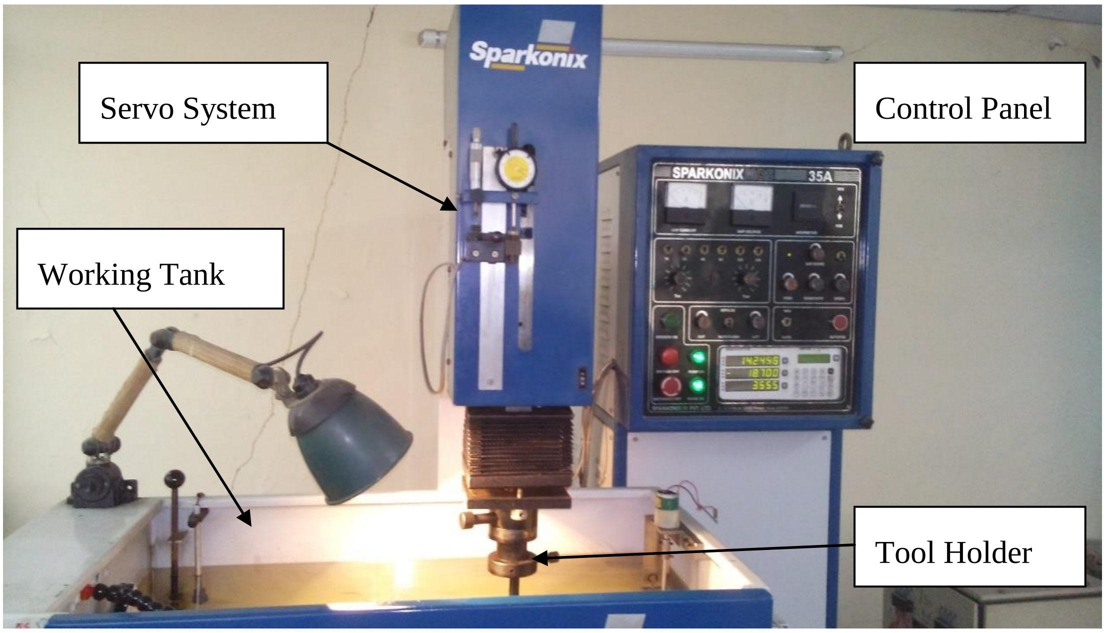

Figure 14 - Pictorial view of EDM machine tool

The Electric Discharge Machine consists of the following parts:

i. Working tank with work holding device
ii. Dielectric reservoir and pump
iii. Control Panel and Display Unit

iv. Tool holder

v. Servo Control for feeding the tool

The Electric Discharge Machine shown in Figure 14 has following specifications:

Table 8 - Specification of EDM machine

Machining Unit	**SN35**
Tank Size(mm)	775x450x325
Table Size (mm)	550x350
Long Cross Travel (mm)	200x200
Quill (mm)	200
Maximum Height of Workpiece (mm)	300
Maximum weight of Workpiece (Kg)	400
Maximum Electrode Weight (Kg)	35
Parallelism of Table surface with Travel	0.02
Squareness of the Electrode Travel	0.02/300
Optimum Working Current (Amp.)	35
Power Connect (KVA) 415V, 3 Phase, 50Hz)	4
Frequency of Pulse Time (KHz)	0.05-250
Capacity (Ltrs.)	260
Motor for Pump (H.P)	1

4.1.1 Working tank with work holding device

The Figure 15 shows the working tank filled with EDM oil and the work holding device (a magnetic chuck) along with the electrode holder. Working tank is used as to the supply the fluid during the process of machining.

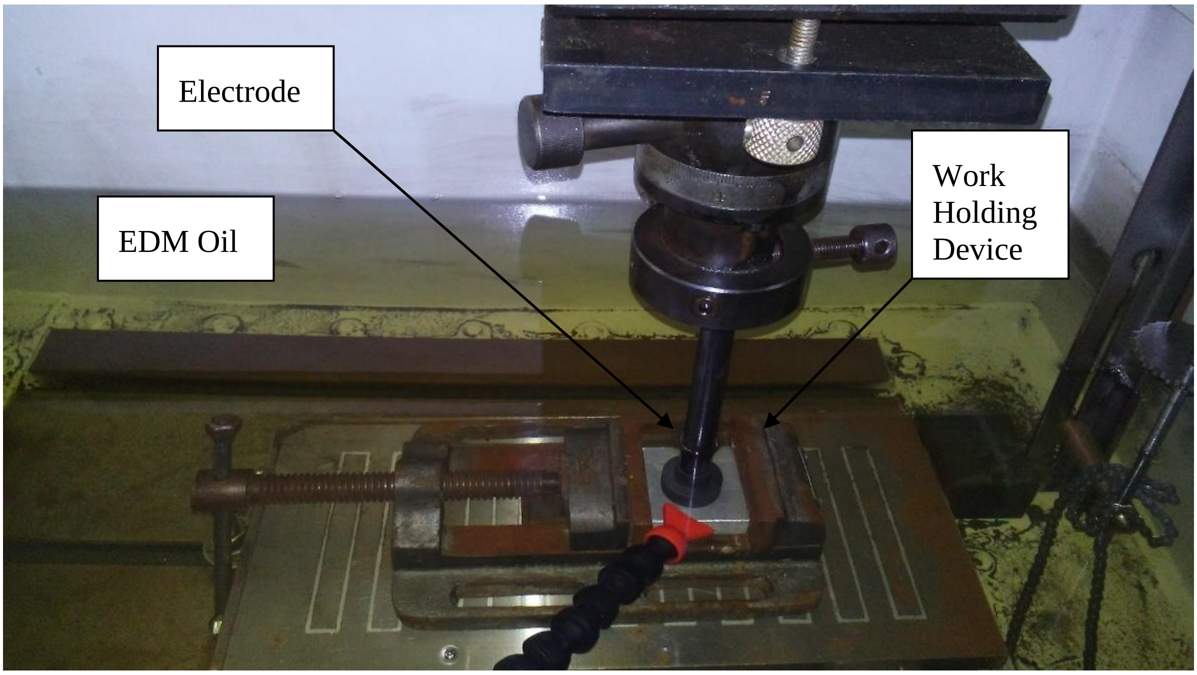

Figure 15 - Working tank with work holding device

4.1.2 Dielectric reservoirs and pump

The dielectric tank is connected to a dielectric pump, an oil reservoir, and a filter system. The pump provides pressure for flushing the work area and moving the oil while the filter system removes and traps debris in the oil. Dielectric reservoir is shown in Figure 16.

Figure 16 - Dielectric reservoirs and pump

4.1.3 Control panel and display unit

A control panel gives DC power supply to provide the electrical discharges, with controls for voltage (V), current (I), pulse duration (T_{on}& T_{off}), duty cycle, frequency, and polarity. The control unit is shown in Figure 17.

Figure 17 - Control panel and display unit

4.1.4 Tool holder

The tool holder in the EDM machine is used to hold the tool during the machining of workpiece as shown in Figure 17.

4.1.5 Servo control

EDM machine is equipped with a servo control mechanism which is controlled by microprocessor connected to the power supply as shown in Figure 14 that automatically maintains a constant gap between the electrode and the workpiece. It is important that there should be no physical contact between the electrode and the workpiece, otherwise arcing could damage the workpiece & electrode. The servomechanism advances the electrode into the workpiece as the operation progresses and senses the work-electrode spacing and controls it to maintain the proper arc gap which is essential to a successful machining operation.

4.3 Mechanism and evaluation of material removal & electrode wear rate

The mechanism of material removal of EDM process is most widely established principle is the conversion of electrical energy it into thermal energy. MRR is the rate at which the material is removed from the workpiece. During the machining process an electrical potential is generated between the tool and the workpiece through the power supply. As the electrode approaches workpiece, the dielectric break down starts taking place in the fluid. Due to this activity, a plasma channel starts forming and sparks jump from the electrode to the workpiece. Each spark produces a tiny crater (as shown in Figure 18) both in the workpiece and electrode material along the cutting path by melting and vaporization.

The MRR is defined as the ratio of the difference in weight of the workpiece before and after machining to the machining time. Similarly EWR is also defined as the ratio of the difference in weight of the electrode before and after machining to the machining time.

$$Material\ removal\ rate\ (in\ mg/min) = \frac{1000X\ (\mathrm{W_i} - \mathrm{W_f})}{t} \qquad (13)$$

Where,

$\mathrm{W_i}$ =Initial weight of workpiece before machining (g)
$\mathrm{W_f}$ =Final weight of workpiece after machining (g)
t = Machining Time = 20 minutes

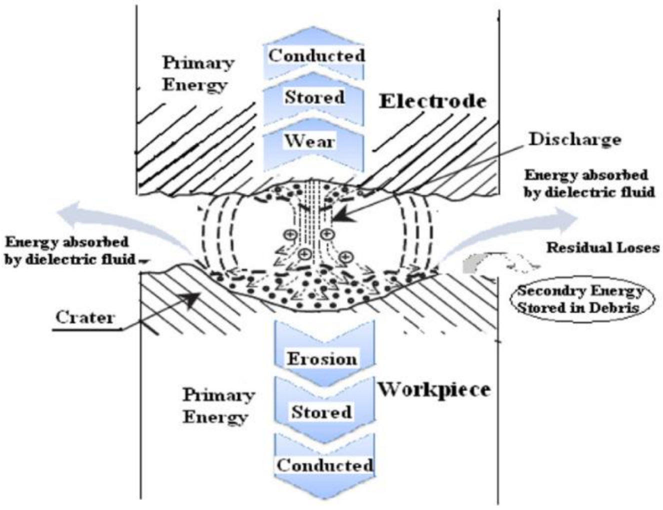

Figure 18 - Mechanism of MRR & EWR [19]

$$Electrode\ wear\ rate\ (in\ mg/min) = \frac{1000X\ \left(E_i - E_f\right)}{t} \qquad (14)$$

Where

$\mathrm{E_i}$=Initial weight of electrode before machining (g)
$\mathrm{E_f}$=Final weight of electrode after machining (g)

4.4 Measurement of surface roughness

Surface Roughness is the measure of the texture of the surface. It is measured in µm. If the value is high then the surface is rough and if low then the surface is smooth. The Ra value, also known as centre line average (CLA) or arithmetic average (R_a) is obtained by averaging the height of the surface above and below the centre line. The values are measured using pocket surf gage (model: pocket surf gage III) shown in Figure 19. The arithmetic mean of two readings is taken as the final value.

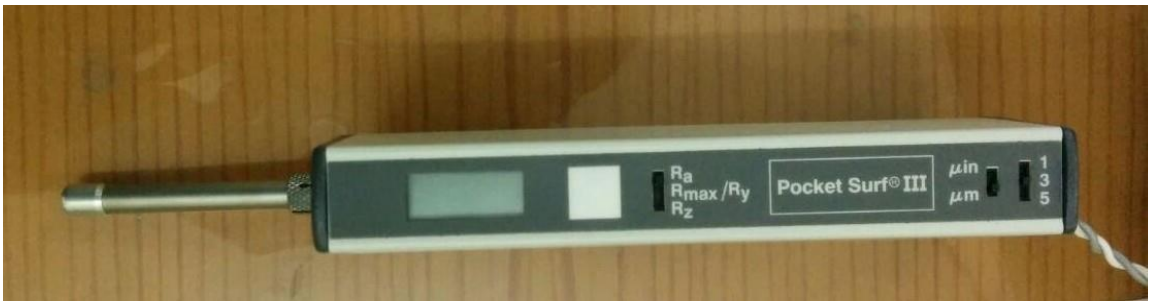

Figure 19 - Surface Roughness Tester

Table 9 - Specification of surface roughness tester

Specification of Surface Roughness Tester	
Measuring Range	R_a - 0.03 µm to 6.35 µm R_{max}/R_y - 0.2 µm to 25.3 µm Rz - 0.2 µm to 25.3 µm
Display Resolution	0.01 µm
Digital Readout LCD	3 digit; “Battery low” signal; “H” and “L” (Measured values out-of-range)
Traverse Speed	5.08mm per second
Probe Type	Piezoelectric
Maximum Stylus Force (within displacement range)	1500mgf/15.0mN
Power	9-volt consumer-type alkaline battery
Operating Temperature	10° to 45°C
Storage Temperature	-20°to 65°C

The pocket surf gage is a portable battery-powered instrument for checking surface roughness with the measured values displayed on a digital readout. The instrument can be used in the laboratory, an inspection area, in the shop andin any position – horizontal, vertical, and upside down. Pocket Surf is used to measure any one of four, switch-selectable, parameters.

- R_a — Average Roughness

- R_{max}/R_y — Maximum Roughness Depth
- R_z — Mean Roughness Depth also called R_t

4.5 Selection of workpiece material

The strength of the any composites material can be controlled by base metal and amount of reinforced material present in the composites. Aluminium and Titanium alloys are the two most commonly used metal matrices because of their low specific gravities and are available in different alloy forms. Al 6061 alloy is a most commonly used as a matrix material because of its high strength and which can be further increased by suitable heat treatment process.

Commonly used reinforcements are silicon carbide (SiC), tungsten carbide, alumina (Al_2O_3), graphite, boron carbide and titanium nitride. Boron carbide (B_4C) could be a substitute to Al_2O_3 and SiC due to its high hardness (the third hardest material after diamond and boron nitride). Boron carbide has properties like high strength, low density (2.52 g/cm^3), extremely high hardness, good wear resistance and good chemical stability.

In this work, Al 6061 is used as a base metal and boron carbide is used as a reinforced particle (particle size 55 µm) to fabricate Al-B_4C composite. The B_4C particles (5% of the wt. of base metal) are reinforced in the Al 6061 metal matrix through stir casting process.

4.6 Fabrication of Al 6061 metal matrix composite

Different techniques have been used by different researchers for fabricating composites. According to the different type of reinforcement particles, the fabrication method differs considerably. Among the several techniques available for aluminium alloy metal matrix composites, stir casting method is most suitable for Al MMCs because of castability of aluminium. This method is also highly economical for the production of MMCs. This method was used by many investigators for fabricating composites.

In this work Al-B_4C MMC was fabricated using a stir casting method. The base metal Al 6061 was melted at 800^{0}C in an electric furnace and boron carbide powder was then added slowly to the molten metal. The boron carbide powder added to the molten metal was pre-heated for 500^{0}C to remove the moisture present (if any) in it. Then the mixer is used to stirrer the molten metal at 300 rpm for 10 minutes. During stirring, magnesium powder was added in small quantities to increase the wettability between metal matrix and reinforcement particles. After the stirring period, crucible was taken outside the furnace and the molten metal with the reinforced particulates was poured into a dried, coated and preheated permanent metallic mould to get the required specimens.

The Figure 20, shows the workpiece (machined & Un- machined) of Al-B_4C MMC with dimensions of 51mm x51mmx12.7mm.

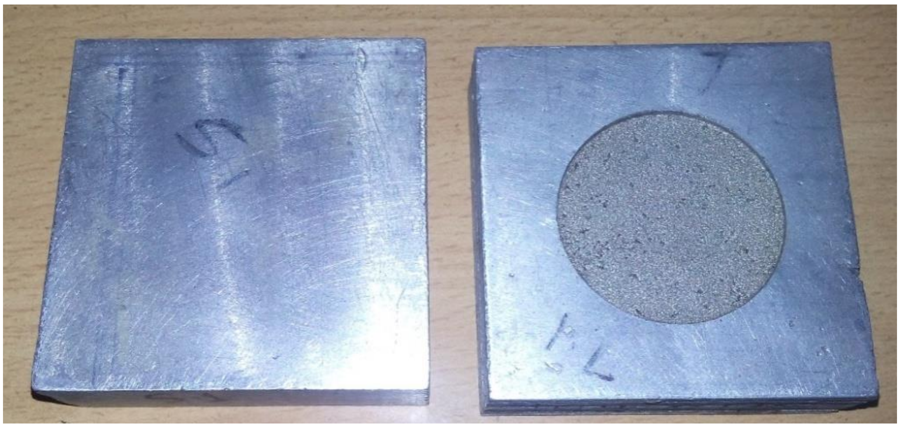

Figure 20 - Machined and unmachined workpiece

Table 10 - Work material specification

Base Material	**Al (%)**	**Si (%)**	**Mg (%)**	**B_4C (%)**	**Particle Size (µm)**
Al 6061	92.7	7.0	0.3	5	55

4.7 Study of microstructure of fabricated composite

The main objective of the microstructure study was to find the distribution of reinforced particles within the matrix. This investigation was performed to confirm the uniform distribution of boron carbide particles in the fabricated composite using Scanning Electron Microscope (SEM). SEM image of the cast composite, as shown in Figure 21, revealed that the reinforcement particles (dark dots) are uniformly distributed within the matrix material.

4.8 Tool material and geometry

EDM tool material should have good electrical conductivity, good machinability, low erosion rate, low electrical resistance, high melting point and high electron emission. Therefore the usual choices for tool (electrode) materials are copper, brass, alloys of zinc and tin, hardened plain carbon steel, copper tungsten and graphite etc. In the present work copper, graphite and EN-19 (tool steel) were used as electrode materials. The shape of the tool electrode was cylindrical having a diameter of 30 mm as shown in Figure 22.

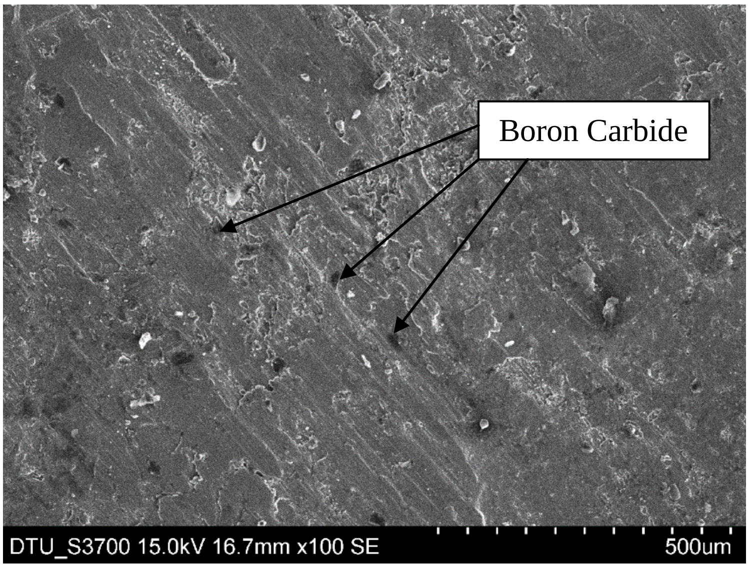

Figure 21 - SEM image of Al-B_4C MMC

The one of the tool material selected for this experiment is copper, which is a ductile metal with high thermal and electric conductivity. It is widely used when high surface finish is required on workpiece. Copper have high machineability as it can be machined by all conventional machining methods like milling, drilling, turning grinding etc. The structural integrity of copper electrodes makes it highly resistant to DC arcing even in poor flushing conditions.

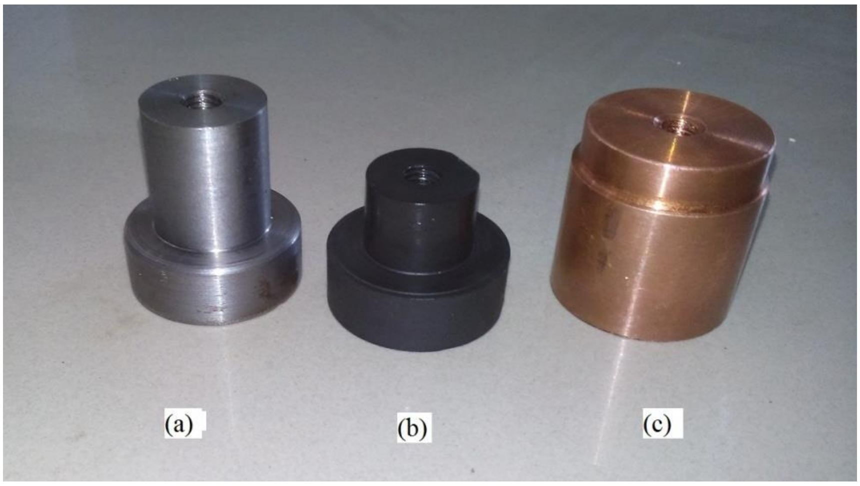

Figure 22- (a)-EN-19 electrode (b)-Graphite electrode (c)-Copper electrode

Second tool material selected for this experiment is graphite, which is the preferred electrode material for 90% of all sinker EDM applications. Graphite has an extremely high melting point (3650^0C). Actually, graphite does not melt at all, but sublimes directly from a solid to a gas and ability to sustain such a high temperature makes graphite an ideal electrode material for EDM process. But graphite has significantly lower mechanical strength properties than metallic electrode materials. It is neither as hard, nor as stiff as metallic electrode materials. However, since the EDM process is one of relatively low macro mechanical forces, these property differences are not often significant. The weight of the electrode becomes very important when the size of electrode is very large and it creates problems in construction and use of the electrode. As graphite has much lower density than copper therefore it becomes the best material for larger electrodes.

Third tool material selected for this experiment is EN-19(tool steel) which contains iron 96.86% and carbon 0.38%. This grade of steel has good ductility and shock and wear resisting properties. EN-19 steel is suitable for elevated temperature applications.

Chapter 5

Experimental Results and Analysis – Taguchi Technique

5.1 Introduction

This chapter uses Taguchi experimental design method. The scheme of carrying out experiments was selected and the experiments were conducted to find out the effect of input process parameters on the output parameters. The experimental results are discussed subsequently in the following sections.

5.2 Introduction of Minitab

For the various analysis purposes Minitab statistical software is used. There is some other statistical software available like SAS, SPSS, R, S-plus etc. Out of large no. of software, Minitab version 16 is selected because of its wide acceptance among researchers, user friendliness and easy availability. This software is available with Minitab worksheet which is similar to the Excel worksheet in tabulated form. It can save the data in worksheet, graph format and project form. It can create Taguchi design as per our level and factor selection. Once results are put up in the worksheet then analysis of Taguchi design can be performed. In this analysis signal to noise ratio is tabulated, factors are given rank based on delta value and main effects plots are extracted. This would be utilized for optimization purpose. This software can predict the signal to noise ratio for comparison purpose. It also can perform regression analysis and analysis of variance (ANOVA).

5.3 Selection of orthogonal array and parameter assignment

For the present experiment the input parameters considered are spark on time (Ton), spark off time (T_{off}), discharge current (I) and electrode material as shown in Table-11. So the design becomes a 3 level, and 4 factorial Taguchi design. L_9 orthogonal array (given in Table-12) was chosen for the experiments to be conducted.

Table 11 - Input Parameters and their Level

Input Parameters	**Current (Amp)**	**Pulse on Time (µs)**	**Pulse off Time (µs)**	**Electrode Material**
Symbol	A	B	C	D
Level 1	2	6	2	Cu
Level 2	4	8	4	EN-19
Level 3	6	10	6	Graphite

Table 12 - L_9 Orthogonal Array [14]

Exp. No.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

5.4 Conduct of experiment

Al-B_4C MMC is machined using SPARKONIK SN 35 (die sinking type) Electric Discharge Machine. Commercial grade EDM oil LL21 was used as a dielectric fluid. External flushing with was used to flush away the eroded materials from the sparking zone. The calculation of material removal rate and electrode wear rate is performed by using electronic balance weight machine. This machine has maximum capacity of 600 gram and accuracy is 0.01g. To ensure validity and accuracy each test is repeated two times (T1 & T2) i.e. trial 1 (T1) and trial 2 (T2) and the average values of MRR, EWR and SR are calculated.

5.5 Experimental results

The average values and the S/N ratios of different experiments for MRR, EWR and SR are given in Table-13 and Table-14 respectively.

Table 13 - Experiment result of trial 1 & trial 2

Exp. No.	Average MRR (mg/min)	Average EWR (mg/min)	Average SR
1.	13.825	0.750	4.415
2.	3.300	1.750	4.580
3.	4.700	0.875	3.650
4.	77.675	1.000	4.925
5.	29.550	0.625	5.415
6.	5.425	2.875	5.280
7.	135.925	3.000	5.945
8.	132.875	1.000	5.860
9.	19.150	1.350	5.405

Table 14 - S/N Ratios of different experiments for MRR, TWR and SR

Expt. No.	S/N ratio of MRR	S/N ratio of EWR	S/N ratio of SR
1.	22.8061	2.0412	-12.8987
2.	7.3395	-4.9485	-13.2441
3.	10.4334	1.0721	-11.2751
4.	37.7478	-0.2633	-13.8706
5.	26.0567	3.9121	-14.6751
6.	8.8146	-10.7119	-14.4557
7.	42.3363	-10.0000	-15.4868
8.	42.4259	-0.9691	-15.3580
9.	25.5465	-2.6304	-14.6600

5.6 Effect of process parameters on MRR, EWR and SR

5.6.1 Analysis and discussion of MRR

The S/N ratios for MRR are calculated by the equation given below. Taguchi method is used to analysis the result of response of machining parameter for higher is better criteria.

$$(S/N)_{HB} = -10\log(MSD)_{HB} \qquad (15)$$

Where,

$$(MSD)_{HB} = \frac{1}{2}\sum_{j=1}^{R}(\frac{12}{yj}) \qquad (16)$$

R = Number of repetitions

The delta values of Current, T_{on}, T_{off} and electrode material are 23.24, 19.31 2.73 and 10.71 respectively, given in Table-15. The case of MRR, it is “Higher is better”, so from this table it can be seen clearly that current is the most important factor then pulse on time (T_{on}) and last is pulse off time (T_{off}).

Table 15 - Response table for S/N ratio higher is better (MRR)

Level	Current	Pulse on Time	Pulse off Time	Electrode Material
1	13.53	34.30	24.68	24.80
2	24.21	25.27	23.54	19.50
3	36.77	14.93	26.28	30.20
Delta	23.24	19.37	2.73	10.71
Rank	1	2	4	3

During the process of EDM, the influence of different machining parameter like current, pulse on time (T_{on}), pulse off time (T_{off}) and electrode materials on MRR is shown (Figure 23) in main effect plot of mean values for MRR.

The discharge current is directly proportional to MRR and it increases monotonically with the increase in current [26].This is expected because with increase in current strong sparks are produces, which produces higher temperature, causing more material to melt and erode from the work piece.

However, MRR decreases monotonically with the increase in pulse on time. It is well known fact that as the pulse on time (T_{on}) increases spark energy increases, due to which MRR increases with increase in pulse on time (T_{on}). MRR usually increases with pulse on time (T_{on}) up to a maximum value after which it starts decreasing. This is due to the fact that with higher T_{on}, more material gets melted at the tool work piece interface, which require proper flushing time but as the value of pulse off time is too short so there is not enough time for the flushing to clear the debris from the inter-electrode gap between the tool and work piece, so arcing take place which result in decreasing the MRR [27]. In this experiment the value of pulse durations are 6, 8, and 10 μs which miss the peak values. So, the plotted graph of pulse on time vs MRR, shows decreasing trend only.

The pulse off time is the time require for the re-establishment of insulation in the working gap or deionization of dielectric at the end of each discharge [28]. At short pulse off time MRR is less due to the fact that with short pulse off time the probability of arcing is very high, because the dielectric in the gap between the work piece and electrode cannot be flushed away properly and the debris particles still remain in the inter electrode gap and this results in arcing, due to which MRR decreases. With the increase in pulse-off time, better flushing of debris take place from the discharge gap, resulting in increase in MRR with increase in pulse off time [27].

From the graph of electrode material vs MRR it is found that graphite electrode is more favorable than the copper and EN-19 electrodes for the machining of Al-B_4C MMCs as MRR is highest for the graphite electrode. It is expected because cathode must be hot enough to permit electrons to absorb energy to escape. The thermo physical properties of graphite are very different from copper and EN-19. When copper and EN-19 are made cathodes they can emit electrons, to carry out the current, only after some of its own material is melted. On the other hand, when graphite is made cathode it is able to emit electrons below its sublimation temperature. Therefore graphite is more stable than copper and EN-19 as cathodes, which promotes higher material removal rates.

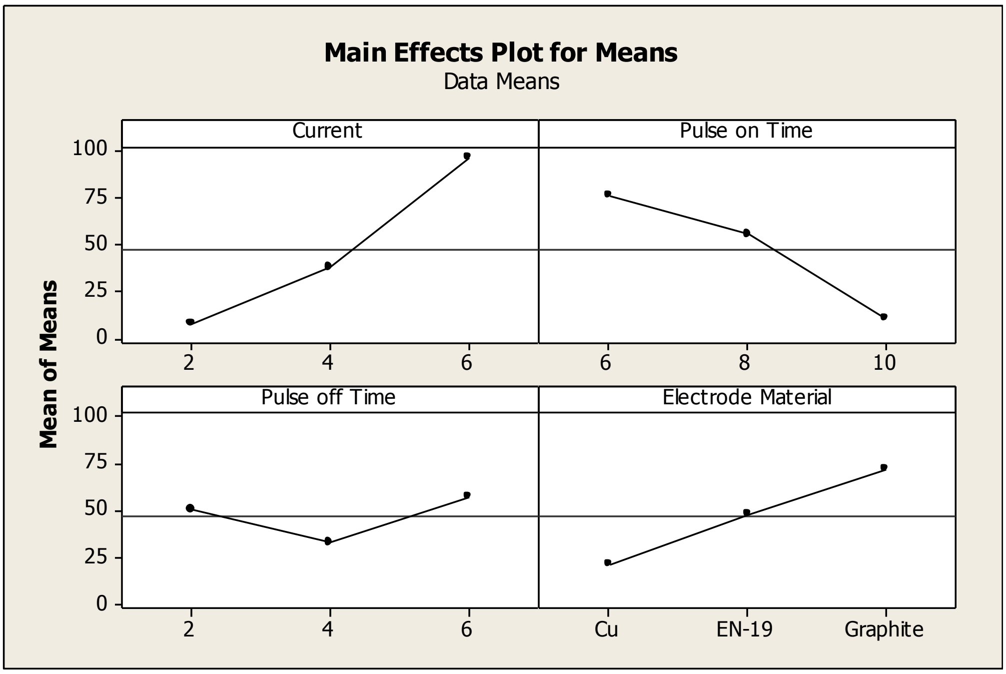

Figure 23 - Effects of Process Parameters on Material Removal Rate (Raw Data)

The experimental results were analyzed using analysis of variance (ANOVA), for identifying the factors significantly affecting the MRR. The analysis was carried out for a significance level of α=0.05, i.e. for a confidence level of 95%.Referring Table-16 it is noticed that factor current has largest contribution to the total sum of squares i.e. 52.1026 %. The factor pulse-on time (T_{on}) and electrode material also have the considerable contribution in total sum of the squares which is 36.1438 % and 11.0293 % respectively.

Table 16 - Analysis of variance (ANOVA) result for S/N ratios for MRR

Parameter	**Degree of Freedom**	**Sum of Squares**	**Mean Sum of Squares**	**F (% Contribution)**
Current	2	812.1453	406.0726	52.1026
Pulse on Time	2	563.3877	281.6938	36.1438
Pulse off Time	2	11.2902	5.6451	0.7243
Electrode Material	2	171.9182	85.9591	11.0293
Total	8	1558.7413	779.3703	100.000

The larger the contribution of any factor to the total sum of squares, the larger is the ability of that factor to influence material removal rate (MRR). So current has maximum effect on material removal rate, Pulse on time (T_{on}) and electrode material have considerable effect on material removal rate whereas pulse off time (T_{off}) has very less effect on MRR.

5.6.2 Optimum design for material removal rate

In the experimental analysis, main effect plot of S/N ratio for MRR is used for estimating the S/N ratio of MRR with optimal design conditions. As shown in Figure 24, MRR has the highest value at level 3 for current, level 1 for pulse on time, level 3 for pulse off time and level 3 for electrode material.

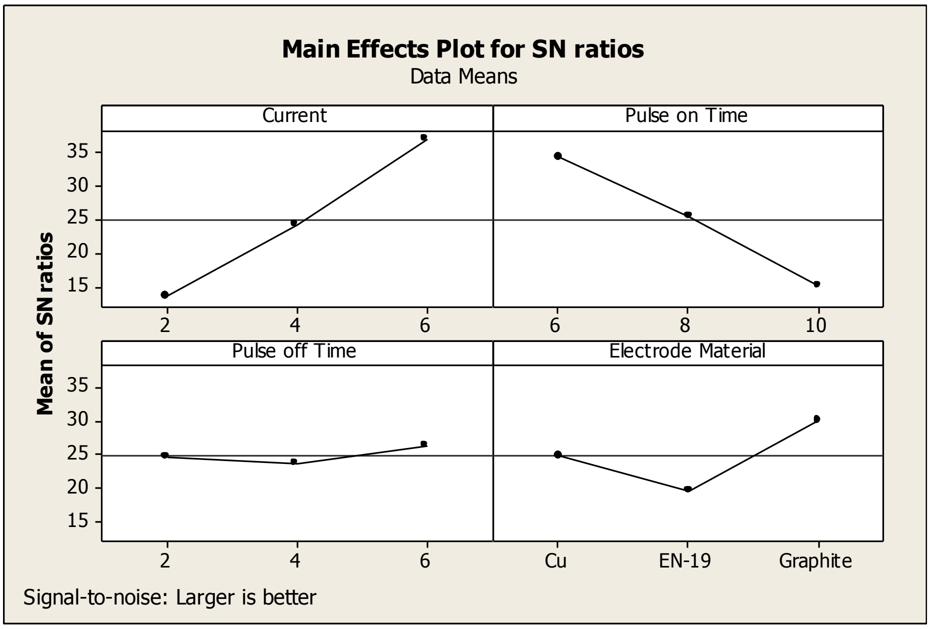

Figure 24 - Effects of Process Parameters on Material Removal Rate (S/N Data)

5.6.3 Analysis and discussion of EWR

5.6.4 Influences on EWR

Since it is always desirable to achieve the lowest electrode wear therefore smaller is better option is selected. The S/N ratio for EWR is calculated by the equation given below.

$$(S/N)_{LB} = -10\log(MSD)_{LB} \tag{17}$$

Where

$$(MSD)_{LB} = \frac{1}{R\sum_{j=1}^{R} y_{21}} \tag{18}$$

R = Number of repetitions

The delta values of current, pulse on time (T_{on}), pulse off time (T_{off}) and electrode material are 3.92145, 3.42157, 1.54133 and 0.66108 respectively, in the response Table-17. This response table shows the effects of input factors on EWR. Here according to ranks, the effects of various input factors on EWR in sequence of its effect are electrode material, current, pulse on time (T_{on}) and pulse off time (T_{off}). That means electrode material affects the EWR at the highest level and pulse off (T_{off}) time at the lowest level.

Table 17 - Response table for S/N ratio smaller is better (EWR)

Level	**Current**	**Pulse on Time**	**Pulse off Time**	**Electrode Material**
1	-0.61173	-2.74070	-3.21327	1.10761
2	-2.35438	-0.66851	-2.61408	-8.55347
3	-4.53318	-4.09008	-1.67194	-0.05343
Delta	3.92145	3.42157	1.54133	0.66108
Rank	2	3	4	1

During the process of EDM, the influence of different machining parameter like current, pulse on time (T_{on}), pulse off time (T_{off}) and electrode materials on EWR is shown (Figure 25) in main effect plot of mean value for EWR.

Increasing the current the tool wear rate is increasing. It is expected because of increases in the current, increases the amount of pulse energy delivered to the machining zone due to which more heat energy is produced between the tool and workpiece interface, which results in increase electrode wear rate [29].

EWR decreases initially with increment in pulse on time but increases with further increase in pulse on time. The main cause of less electrode wear is deposition of black carbon layer on the tool surface which migrates from the dielectric to the electrode which results in reduction in electrode wear rate [30].The increase in EWR with further increase in pulse on time is expected because in EDM, the electro-discharge plasma channel is composed of electron and cation flows. At short pulse on time, the electron flow is dominant in the plasma channel and hence the positive electrode (workpiece), being more attacked by the electrons, and hence has a higher wear rate. However, the ratio of cation flow in the plasma channel increases (which are 1837 times heavier than electrons) with increasing pulse duration. Hence, electrode wear rate (-ve electrode) increases with increasing pulse duration [30]. EWR slightly decreases initially with increment in pulse off time (T_{off}) upto 4μs but increases with further increase in pulse off time (T_{off}).Increase in EWR is expected fact that with short pulse off time the probability of arcing is very high, because the dielectric in the gap between the work piece and electrode cannot be flushed away properly and the debris particles still remain in discharge gap and this results in arcing, due to which EWR decreases. With the increase in pulse-off time, better flushing of debris take place from the inter-electrode gap, resulting in increase in EWR [26].

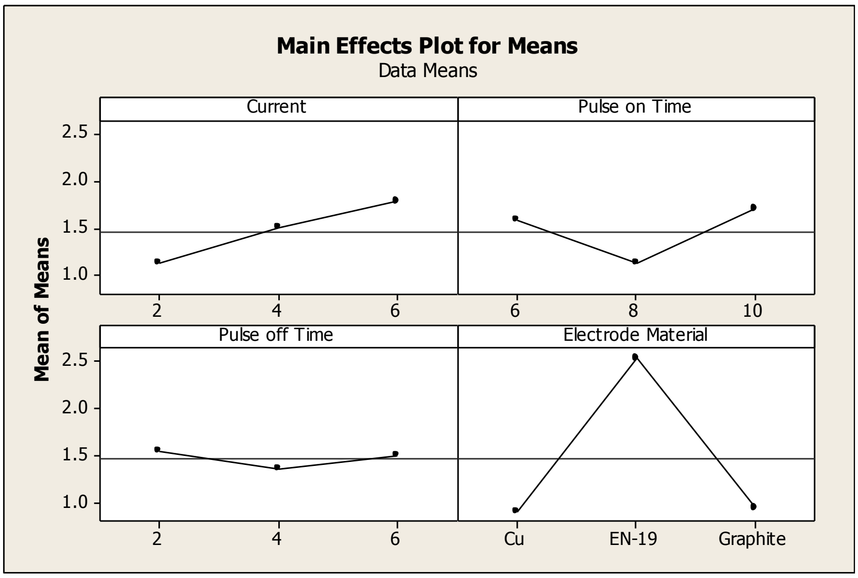

Figure 25 - Effects of Process Parameters on Electrode Wear Rate (Raw Data)

From the graph of electrode material vs EWR it can be seen that the EN-19 electrode has given the highest EWR followed by graphite and copper. Because graphite has higher melting point (3650^0C) while copper have very high thermal conductivity (i.e. 401W/mk) higher the thermal conductivity better will be the dissipation of energy accumulated during each discharge)as compare to EN-19 therefore EN-19 gives the highest electrode wear rate as compared to copper and graphite.

The experimental results were analyzed using analysis of variance (ANOVA), for identifying the factors significantly affecting the EWR. The analysis was carried out for a significance level of α=0.05, i.e. for a confidence level of 95%.Referring Table-18 it is noticed that factor electrode material has largest contribution to the total sum of squares i.e. 78.138 %. The factor current and pulse-on time (T_{on}) also have the considerable contribution in total sum of the squares which is 10.9490% and 8.4248% respectively. The pulse off time (T_{off}) has much less contribution of 1.7124%. The larger the contribution of any factor to the total sum of squares, the larger is the ability of that factor to influence EWR. So electrode material has maximum effect on EWR, while current and pulse on time (T_{on}) has considerable effect on EWR whereas pulse off time (T_{off}) has very less effect on EWR.

Table 18 - Analysis of variance (ANOVA) result for S/N ratios for EWR

Parameter	**Degree of Freedom**	**Sum of Squares**	**Mean Sum of Squares**	**F (% Contribution)**
Current	2	23.1617	11.5809	10.9490
Pulse on Time	2	17.8220	8.9110	8.4248
Pulse off Time	2	3.6223	1.8112	1.7124
Electrode Material	2	166.9352	83.4676	78.138
Total	8	211.5412	105.7706	100.0000

5.6.4 Optimum design for EWR

Since TWR is an important factor because it affects dimensional accuracy and the shape produced, it is related to the melting point of the electrode tool materials.

In the experimental analysis, main effect plot of S/N ratio for EWR is used for estimating the S/N ratio of EWR with optimal design conditions. As shown in Figure 26, EWR has the lowest value at level 1 for current, level 2 for pulse on time, level 2 for pulse off time and level 1 for electrode material.

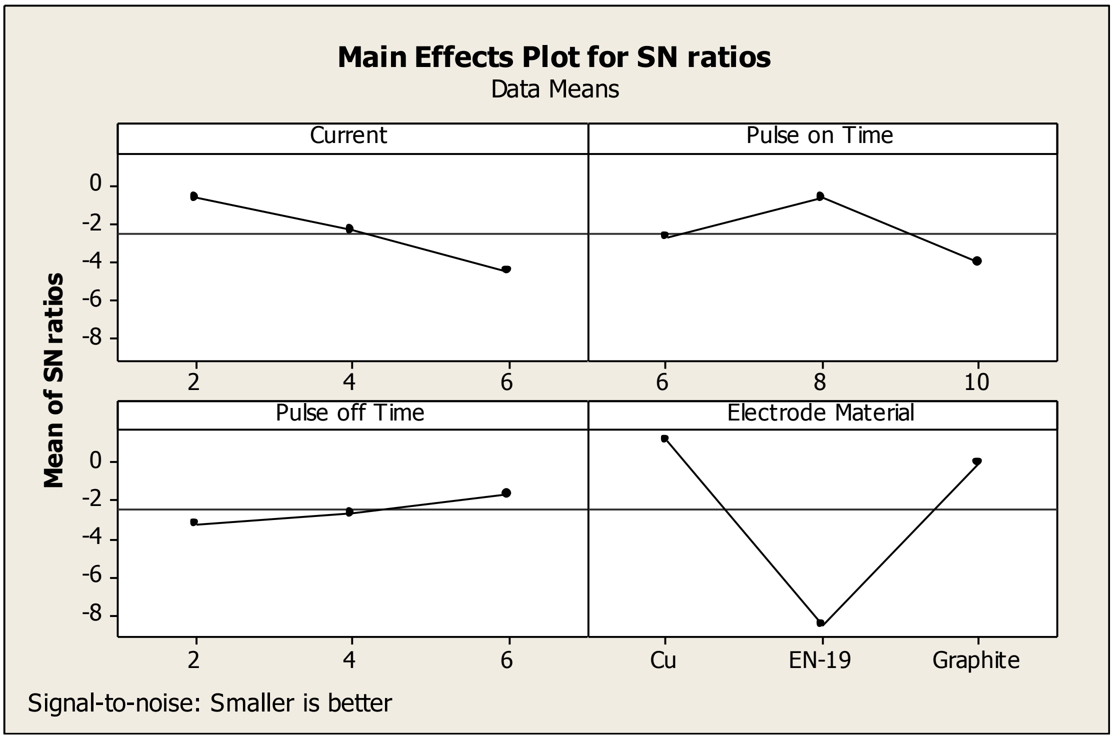

Figure 26 - Effects of Process Parameters on Electrode Wear Rate (S/N Data)

5.6.5 Analysis and discussion of SR

5.6.6 Influences on SR

Since it is always desirable to achieve the lowest surface roughness therefore smaller is better option is selected. The S/N ratios for SR are calculated by the equation given below.

$$(S/N)_{LB} = -10\log(MSD)_{LB} \qquad (19)$$

Where

$$(MSD)_{LB} = \frac{1}{R\sum_{\mathrm{j=1}}^{\mathrm{R}} \mathrm{y}_{21}} \qquad (20)$$

R = Number of repetitions

The delta values of current, pulse on time (T_{on}), pulse off time (T_{off}) and electrode material are 2.70, 0.96, 0.43 and 0.89 respectively, in the response Table-19. This response table shows the effects of input factors on SR. Here according to ranks, the effects of various input factors on SR in sequence of its effect are current, pulse on time (T_{on}), electrode material and pulse off time (T_{off}). That means current affects the SR at the highest level and pulse off (T_{off}) time at the lowest level.

Table 19 - Response table for S/N ratio smaller is better (SR)

Level	**Current**	**Pulse on Time**	**Pulse off Time**	**Electrode Material**
1	-12.47	-14.09	-14.24	-14.08
2	-14.33	-14.43	-13.92	-14.40
3	-15.17	-13.46	-13.81	-13.50
Delta	2.70	0.96	0.43	0.89
Rank	1	2	4	3

During the process of EDM, the influence of different machining parameter like current, pulse on time (T_{on}), pulse off time (T_{off})and electrode materials on EWR is shown (Figure 27) in main effect plot of mean value for SR.

Surface roughness of machined surface increases with increase in current. It is expected because higher the current, higher will be the energy content per spark. Due to which higher depth craters are formed on the surface of the workpiece which results in high surface roughness [29].

Pulse-on time has influencing effect on SR. From the graph of pulse on time (T_{on}) vs SR it can be seen that SR increases initially with increment in pulse on time (T_{on}) but decreases with further increase in pulse on time (T_{on}). With the increase in pulse on time (T_{on}) spark energy increases causes the enlargement of pores created through electrical discharge on the surface of workpiece due to which SR increases with increase in pulse on time (T_{on}) and a further increase of pulse on time beyond 8µs results in the decrease in surface roughness [30].

From the graph of pulse off time (T_{off}) vs SR it can be seen that SR is decreasing with pulse off time upto a minimum level and then remains almost constant with pulse off time. It is expected because with the increase of pulse off time, the no. of surface pores decreases in number and surface roughness decreases [31].

From the graph of electrode material vs SR it can be seen that the EN-19 graphite electrode has given the highest SR and graphite and copper provide approximately the same surface finish. Using very fine grain graphite the surface finish obtained is comparable to that obtained from copper.

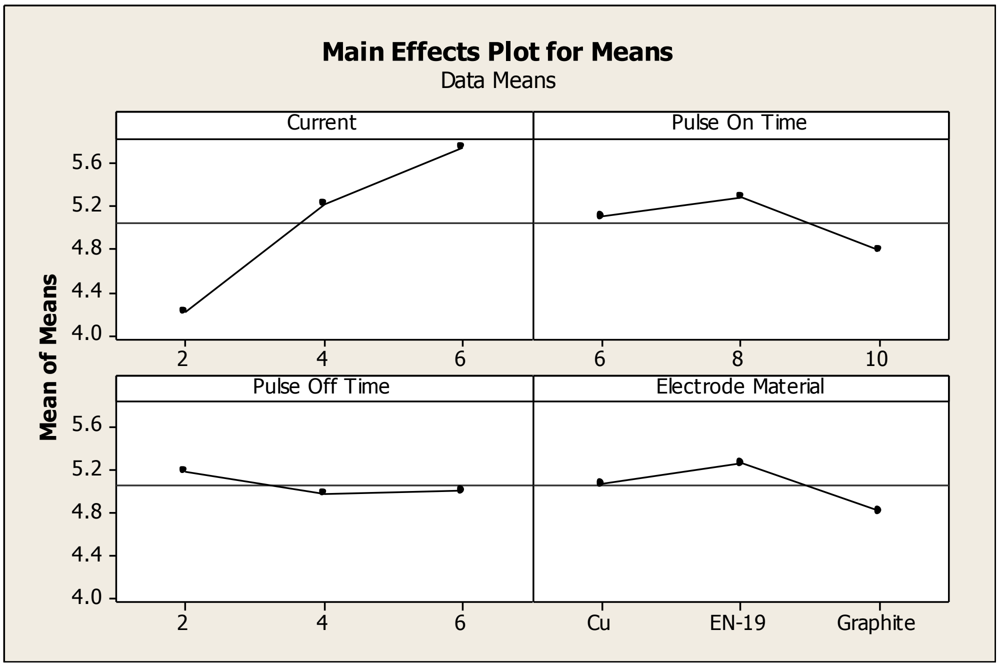

Figure 27 - Effects of Process Parameters on Surface Roughness (Raw Data)

The experimental results were analyzed using analysis of variance (ANOVA), for identifying the factors significantly affecting the SR. The analysis was carried out for a significance level of $\alpha=0.05$, i.e. for a confidence level of 95%.Referring Table-20 it is noticed that factor current has largest contribution to the total sum of squares i.e. 79.4677 %. The factor pulse-on time (T_{on}) and electrode material also have the considerable contribution in total sum of the squares which is 9.315 % and 8.5763 % respectively. The pulse off time (T_{off}) has much less contribution of 2.0245 %.

The larger the contribution of any factor to the total sum of squares, the larger is the ability of that factor to influence SR. So current has maximum effect on SR, while pulse on time (T_{on}) and electrode material has considerable effect on SR whereas pulse off time (T_{off}) has very less effect on SR.

Table 20 - Analysis of variance (ANOVA) result for S/N ratios for SR

Parameter	**Degree of Freedom**	**Sum of Squares**	**Mean Sum of Squares**	**F (% Contribution)**
Current	2	11.4268	5.7134	79.4677
Pulse on Time	2	1.4281	0.7140	9.9315
Pulse off Time	2	0.2911	0.1456	2.0245
Electrode Material	2	1.2332	0.6166	8.5763
Total	8	14.3792	7.1896	100.0000

5.6.7 Optimum design for SR

In the experimental analysis, main effect plot of S/N ratio for SR is used for estimating the S/N ratio of SR with optimal design conditions. As shown in Figure 26, EWR has the lowest value at level 1 for current, level 3 for pulse on time, level 3 for pulse off time and level 3 for electrode material.

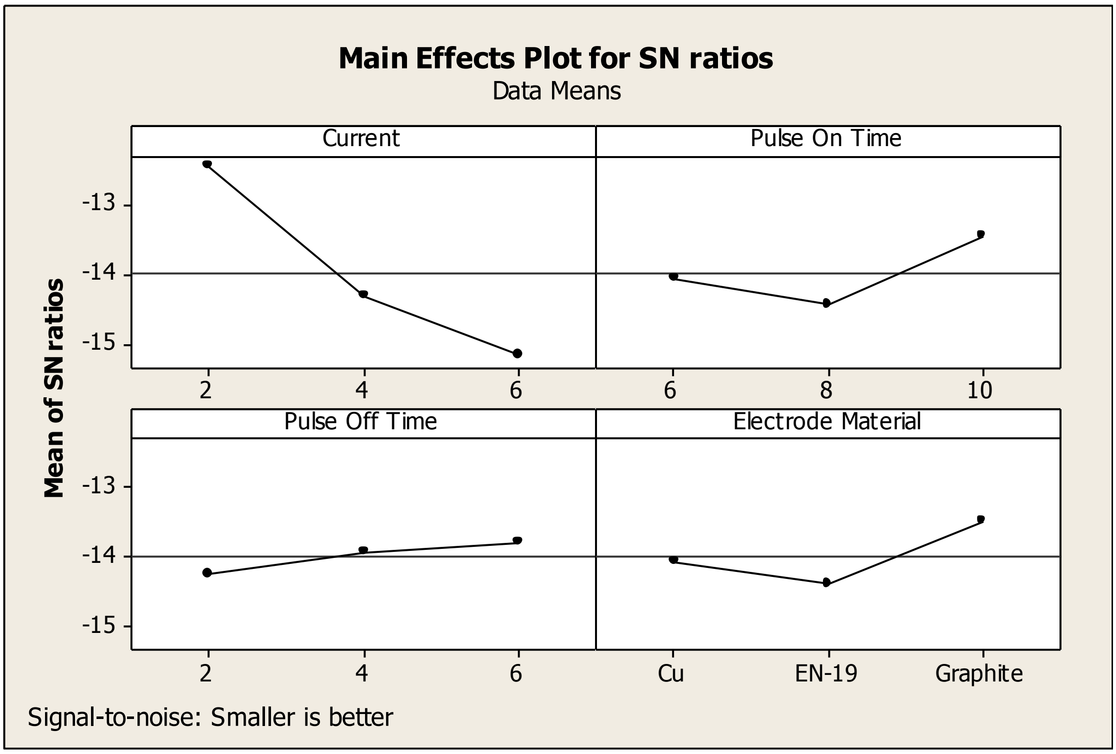

Figure 28 - Effects of Process Parameters on Surface Roughness (S/N Data)

Chapter 6
Conclusions

EDM is a complex machining process having large numbers of factors affecting the process performance e.g. current, pulse on time, pulse off time, gap voltage, flushing pressure, electrode material and electrode size. But for current study the main factors considered are: current, pulse on Time (T_{on}), pulse off time (T_{off}), and electrode materials on EWR SR and MRR has been investigated. The result obtained from the experiment shows that current, pulse on time and electrode material has significant effect on MRR, EWR and SR. The result of the present work reveals that proper selection of input parameters selection play a major role in optimizing electric discharge machining.

The following are the conclusions derived from the present investigations after conducting the statistical analysis.

i) Based on the results of ANOVA analysis it has been seen that current and pulse on time were the most significant factors affecting material removal rate. MRR of the composite increases with increase in current while it decreases with increase in pulse on time. It was found that MRR of the composite is decreasing initially with increase in pulse off time and later it was increasing. It was also found that MRR is highest for the graphite electrode.

ii) Based on the results of ANOVA analysis it has been seen that electrode material and current are most significant parameter for electrode wear rate. Electrode wear rate increases linearly with increase in current.EWR of the composite is decreasing initially with increase in pulse on time and later it was increasing with pulse on time. It was found that EWR of the composite slightly decreases initially with increment in pulse off time but increases with further increase in pulse off time. It was also found that EN-19 electrode has given the highest EWR followed by graphite and copper.

iii) Based on the results of ANOVA analysis it has been seen that current and pulse on time are most significant parameters for surface roughness. Surface roughness of the composite during machining increases with increase in current while it increases initially with increment in pulse on time but decreases with further increase in pulse on time. It was found that SR is decreasing with pulse off time upto a minimum level and then remains almost constant with pulse off time. It was also found that graphite electrode has given the lowest SR.

iv) For maximum MRR, **A3B1C3D3** levels must be selected, for minimum EWR, **A1B2C2D1** and for lowest SR, **A1B3C3D3** levels must be selected and their corresponding values are given in Table-21.

Table 21 - Optimum levels of input parameters

Parameter	**MRR**	**EWR**	**SR**
Current (A)	6	2	2
Pulse on Time(B)	6	8	10
Pulse off Time (C)	6	4	6
Electrode Material(D)	Graphite	Copper	Graphite

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