CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF COMPOSITE AND EDM PROCESS

Nowadays, composite materials play an important role in the engineering fields as well as advanced manufacturing technology in response to unprecedented needs from advanced technology due to rapidly advancing activities in automotives, aerospace and defense fields, nuclear fields, aircrafts industries. These composites have low specific properties especially superior in modulus and strength to many conventional engineering materials. Generally, these novel materials include high performance composites viz. reinforced composites. Continual advancements have led to the use of composite materials in more diversified applications. Generally, the importance of composites as engineering materials is reflected by the fact that out of over 1600 engineering materials available in the current market more than 200 are composites (Manocha & Bunsell 1980).

In 1970, the English scientist, Priestly, first detected the erosive effect of electrical discharges on metals. More recently, during research Soviet scientists, Lazarenko and Lazarenko decided to exploit the destructive effect of electrical discharge and develop a controlled method of metal machining. In 1943, they announced the construction of the first spark erosion machine. The spark generator introduced in 1943, known as the Lazarenko circuit, has been employed over many years in power supplies for EDM machine and improved form is being used in many current applications (Lazarenko 1943). The EDM process can be compared with the traditional cutting process, except that in this case, a properly shaped electrode, with a precision controlled feed movement is employed in place of the cutting tool and the cutting energy is provided by means of short duration electrical
impulses. Thus, it plays a vital role in the machining of tools, molding dies made up of hard steels, tungsten carbide and satellites. Alloys used in the aeronautics industries such as hastalloy, nimonic could be machined conveniently by this process (Kalpajian & Schmid 2003).

1.2 COMPOSITE

A composite material is a macroscopic combination of two or more than two different materials, having a recognizable interface between them. The individual materials that make up composites are called constituents. Generally, most composites have two constituent materials: a binder or matrix (Polymers, Metals or Ceramics) and reinforcement (Particles, Flakes and or fillers) (Reinhart & Clements 1987). The reinforcement is usually much stronger and stiffer than the matrix and gives the composite its excellent properties. The matrix holds the reinforcements in an orderly pattern. Because the reinforcements are usually discontinuous, the matrix also helps to transfer load among the reinforcements. Composites are not only used for their structural properties, but also for thermal, tribological and environmental applications. The composite is defined as “The composites are compound materials which differ from alloys by the fact that the individual components retain their characteristics but are so incorporated into the composite as to take advantage only of their attributes and not of their shortcomings” Berghezan (1966).

1.2.1 Classification of Composites

Generally, composites are classified into two major distinct levels viz. the first type of classification is made with respect to the matrix constituent. The prime composite classes include metal-matrix composites, organic-matrix composites and ceramic-matrix composites Bhargava (2004). The term “organic-matrix composite” is commonly assumed to include two
classes of composites: polymer-matrix composites and carbon-matrix composites (generally referred to as carbon-carbon composites). In each type of systems, the matrix is typically a continuous phase throughout the component (Manocha & Bunsell 1980). The second level of classification refers to the reinforcement form-fiber reinforced, particle reinforced and structural composites.

In particle reinforced composites, the equal dimension of particle is mixed in the composite equally in all direction. In fiber-reinforced composites, the fiber (i.e. a large length-to-diameter ratio) is introduced in the matrix in order to improve the mechanical properties. Structural composites are combinations of homogeneous materials and composites. Examples for these three groups include concrete, combination of cement and aggregate, which is a particulate composite; fiberglass, combination of glass fibers imbedded in a resin matrix, which is a fiber composite; combination of plywood and alternating layers of laminate veneers, which is a laminate composite. Particle reinforced composite can be further classified under two subgroups: (i) large particle and (ii) dispersion strengthened composites. The distinction between these is based upon reinforcement or strengthening mechanism Berghezan (1966).

**Fiber-reinforced composites:** The fibre reinforced composites are strong fibers imbedded in a softer matrix to produce products with high strength-to-weight ratios. The matrix material transmits the load to fibers, which absorb the stress.

**Polymer-matrix composites (PMCs):** Polymer Matrix Composites are composed of a matrix from thermoset (Unsaturated polyester (UP), Epoxy) or thermoplastic (PVC, Nylon, Polystyrene) and embedded glass, carbon, steel or Kevlar fibers (dispersed phase) Trostyanskaya (1995).
Ceramic-matrix composites (CMCs): This is the least common composite matrix. Aluminium oxide and silicon carbide are the materials that can be embedded with fibers for improved properties especially in high temperature applications Chawla (2003).

Metal-matrix composites (MMCs): Metal matrix composite is a combination of an alloy or metal and reinforcements. Matrix material distinguishes the MMC from the unreinforced matrix in terms of higher strength, improved elastic modulus, higher service temperature, increased wear resistance, improved electrical and thermal conductivity, low coefficient of thermal expansion and high vacuum environmental resistance. These properties can be obtained with the proper choice of matrix and reinforcement. The prime function of the matrix is to transfer and distribute the load to the reinforcement. This load transfer method depends on the bonding which depends on the type of matrix and reinforcement and the fabrication technique (Suresh et al 1993). The typical applications of MMCs include their use in fabrication of satellite, missile, helicopter structures, structural support, piston, sleeves and rims, high temperature structures, drive shaft, brake rotors, connecting rods, engine block liners, various types of aerospace and automotive applications, etc. Clyne (2000).

1.3 PRODUCTION OF METAL MATRIX COMPOSITE

In recent decades, the prospective of metal-matrix composite for significant improvement in performance over conventional alloys and other materials has been documented extensively. Still, their production costs are relatively high. Nowadays there are several fabrication techniques available to produce the MMC materials; and there is no unique route in this respect. Processing technique needs the fundamentals about the MMCs, to determine their physical and mechanical properties. The processing methods used to produce metal matrix composite can be classified as follows:
1.3.1 Liquid phase fabrication

Liquid state processing of metal matrix composites finds broad application because of the advantages related in terms of lower cost involvements for getting liquid metals than metal powder, possibility of producing different complex shapes using liquid metals with significant ease by adopting methods developed already in the casting industries. Some fabrication process reported by researchers are infiltration (Kevorkijian 2004), (Bahraini et al 2010), dispersion (Sutherland & Gibeling 1992), spraying (Sansoucy et al 2008), In-situ fabrication (Man et al 2002), Squeeze casting (Cayron et al 1999), Stir casting (Gopalakrishnan & Murugan 2012) and compocasting (Sajjadi et al 2012).

1.3.2 Solid phase fabrication

Solid state fabrication of metal matrix composites is used to obtain the highest mechanical properties in the resulting metal matrix composites. Generally, the discontinuous reinforcement metal matrix composites are processed in this route to get improved mechanical properties. This is due to segregation effects and brittle reaction product formation is a minimum as against the liquid state processing method. In the present day, some fabrication methods of metal matrix composite are diffusion bonding (Muratoglu et al 2006) and powder metallurgy (Scudino et al 2009), (Tatar & Ozdemir 2010).

1.3.3 Vapor state processing

Vapor deposition is a prime process where the matrix is deposited from the vapor phase into individual reinforcement elements of the ingredient. It may also be noted that there is minimum or no mechanical disturbance of interfacial region and large adhesion in between reinforcement and matrix
without any chemical reaction. In these fabrication methods, the matrix is deposited by plasma spraying (Hyun-Ki Kang & Suk Bong Kang 2006) or by physical vapor deposition (Tither et al 1995) or by chemical vapor deposition (Tien-Chai Lin & Min-Hsiung Hon 2008).

1.4 ADVANTAGES OF METAL MATRIX COMPOSITE Benedict (1987)

i. Increased strength-to-density ratio and stiffness-to-density ratio.

ii. Improved fatigue resistance and lower creep rate.

iii. Good elevated temperature properties.

iv. Lowered coefficients of thermal expansion.

v. Increased wear resistance and radiation resistance.

vi. Improved temperature capability with fire resistance.

vii. Increased transverse stiffness and strength.

viii. No moisture absorption and no out gasing.

ix. Improved electrical and thermal conductivities.

x. Better fabricability of whisker and particulate-reinforced MMCs with conventional metal working equipment.

1.5 LIMITATIONS OF METAL MATRIX COMPOSITE Benedict (1987)

a. High material cost.

b. Relatively immatured technology.
c. Highly complex fabrication methods for fiber-reinforced systems (except for casting).

d. Only limited service experience.

1.6 APPLICATIONS OF METAL MATRIX COMPOSITE
Benedict (1987)

a. Commercial aircraft

Used for air conditioning duct, radar dome, landing gearbox, seats, floorings, window reveals, ceiling panels, propeller blades and nose, wing body, elevators, ailerons, air brake, etc.

b. Military aircraft

Used for speed brake, elevators, ailerons, landing gear doors, horizontal stabilizers, etc.

c. Missiles

Used for remote piloted vehicles, filament wound rocket motors, wings, rotor cases. It is also used for antennas, struts, support trusses for telescopes, storage tanks for gases and fluids at cryogenic temperature, etc.

d. Automobile and trucks

Used for drive shaft, bumpers, door and window frames, starter motor commentators, body panels, radiator and other hoses, drive chains, etc.
e. **Electrical and electronics**

Used for microphone housing, miniature-electronic card holder, ribs to protect printed circuit boards, parabolic antenna, etc., electrical equipments-switch casing, cable and distribution cabinets, boxes, etc.

f. **Marine applications**

Used for small boat hulls, solar domes, masts, tanks, decks, submarine masts, spinnaker pole on the racing hatch, plates in nuclear submarine lead acid batteries, etc.

g. **Sporting equipments**

Used for tennis rackets, golf club shafts, bicycle components such as wheel, frame forks, handlebars, pedal crank arms, package carriers, fenders, etc.

f. **Automobile industry**

Valve train, piston rod, piston and piston pin, covers, cylinder head, crankshaft main bearing, engine block: part-strengthened cylinder blocks), comparable construction unit characteristics are attainable only with the application of powder metallurgical aluminium alloys or when using heavy iron pistons. The reason for the application of composite materials potential applications are in the area of undercarriages, Transverse control arms and particle-strengthened brake disks, which can be also applied in the area of rail mounted vehicles, e.g. for undergrounds and railway. Figure 1.1 shows the general applications of metal matrix composite.
1.7 NEEDS OF EDM PROCESS FOR MACHINING OF MMC

Traditional or conventional machining such as milling, drilling and turning shows ineffectiveness in machining of advanced materials. The traditional machining cause serious tool wear due to abrasive nature of reinforcing B₄C particles, thereby shortening the life of the tool. In the general view of high tool wear and high tool costs of tooling that are experienced with conventional machining due to matrix-powder two phase structure, many difficulties are encountered in machining of composites e.g. delamination and powder splitting.
Hence, the non-contact material removal process offers an attractive alternative. Non–conventional machining methods or non–traditional machining process are normally selected in wider engineering areas due to their ability to machine complex profiles on difficult–to–cut especially very hard materials. The non–conventional machining processes smoothly cut the difficult–to–cut materials such as die steels, metal matrix composites, tool steels as there is no direct contact between work piece and tool (Senthilkumar et al 2009). In general, the non-conventional processes such as Laser Beam Machining (LBM), Electric Discharge Machining (EDM), Abrasive Water Jet machining (AWJ), Electro Chemical Machining (ECM) offers effective alternatives machining for conventional machining process (Muller & Monaghan 2000). Generally, material with high strength and high hardness such as tool steels, super alloys, composites and advanced ceramics with close precision and surface finish can be done by electric discharge machining successfully (Lauwers et al 2007). Thus in the present research work, EDM becomes an optimal choice in machining of AA6061-B$_4$C$_p$ composite owing to its easy operation and production of high quality products (Ho & Newman 2007).

1.8 INTRODUCTION OF EDM PROCESS

EDM has been a mainstay of manufacturing for more than six decades, providing unique capabilities to machine “difficult-to-machine” materials with desire shape, size and required dimensional accuracy (Abbas et al 2007). Its idiosyncratic attribute of using thermal energy to machine electrically conductive materials, high hardest materials, has been an advantage in the manufacturing of mould, die, automotive and aeronautic components. Though EDM has become a well-known technology and generally used in manufacturing of mechanical works, yet its low efficiency and poor surface finish have been the vital matter of concern.
Hence, the improvements and investigations of the process are still going on, since no such process exists, which could productively replace the EDM. It is the most broadly used non-traditional machining process. Despite of the fact that the mechanism of material removal of EDM process is not yet totally understood and is still arguable Schumacher (2004).

1.8.1 Working Principle of EDM Process

Electric Discharge Machining process is a non-traditional machining process and the metal is removed due to the conversion of electrical energy into thermal energy through a series of discrete electrical discharges occurring between the electrode and work piece immersed inside a dielectric medium and separated by a small gap (McGeough 1988). In this process, the material is removed from the work piece by localized melting and even vaporization of material. A thin gap about 0.025mm is maintained between the tool and work piece by a servo system. Generally, kerosene, EDM oil and deionized water are usually used as dielectric fluids and although gaseous dielectrics are also used in certain cases. The line diagram of Electric Discharge Machining process is shown in Figure 1.2.
When the voltage across the gap becomes adequately high it discharges through the gap in the form of the spark. As positive ions and electrons are accelerated, producing a discharge channel that becomes conductive. Then, it is just at this point when the spark jumps causing collisions between ions and electrons and creating a channel of plasma.
A sudden drop of the electric resistance of the previous channel allows that current density reaches high values producing an increase of ionization and the creation of a powerful magnetic field. The moment spark occurs sufficiently pressure developed between work and tool as a result of which a high temperature is reached at such high pressure and temperature that some metal is melted and eroded. Such localized extreme rise in temperature leads to material removal. The line diagram of the spark initiation in EDM process is shown in Figure 1.3. Material removal occurs due to instantaneous vaporization of the material as well as due to melting. The molten metal is not removed completely but only partially. As the plasma channel collapse, it generates pressure or shock waves, which evacuates the molten material forming a crater of removed material around the site of the spark (Pandey & Shan 1999).

1.8.2 Characteristics of EDM Process

1.8.2.1 Discharge current

Current is measured in terms of ampere allowed per cycle. Generally, discharge current is directly proportional to the Material removal rate.

1.8.2.2 Pulse on time

Pulse on time is the duration of time (\(\mu s\)), the current is allowed to flow per cycle. Material removal from work piece is directly proportional to the amount of energy applied during this on time. This energy is actually controlled by the peak current and the length of the on time. The pulse waveform of controlled pulse generator is shown in the Figure 1.4.
1.8.2.3 Pulse off time

Pulse off time is the duration of time ($\mu$s) between the sparks. During this period, there is no spark to the system. This time allows the molten material to solidify and to be washed out of the arc gap. This parameter affects the speed and the stability of the cut. Thus, if the off time is too short, it will cause sparks to be unstable. A line diagram of actual profile of a single EDM pulse is given in Figure 1.5.

![Figure 1.4 Pulse waveform of controlled pulse generator, McGeough (1988)](image)

![Figure 1.5 Actual profile of a single EDM pulse (Fuller & John 1996)](image)
1.8.2.4 Voltage

Voltage is a potential that can be measured by volt and it also affect the material removal rate allowed per cycle.

1.8.2.5 Duty cycle

Duty cycle is defined as 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 (ontime and pulse off time).

\[
\text{Duty cycle} = \frac{\text{Pulse on time}}{\text{Pulse on time} + \text{Pulse off time}}.
\]

1.8.2.6 Gap size

Arc gap is defined as the distance between the work piece and electrode during the process of EDM. It may be known as spark gap. Normally, the spark gap can be maintained by servo system. In EDM process, the size of the gap is maintained by the servo control system whose motion is controlled by gap width sensors. They control the motion of the ram head or the quill which in turn governs the gap size. Normally, the values of the gap size are between 0.010 to 0.050 mm, although gap sizes as small as several hundred to several thousands of micrometers can be found depending on the application, current, voltage and the die-electric media. The gap size between tool and work piece governs the possibility of sparking and arcing.

1.8.2.7 Polarity

Polarity means the electrical conditions determining the direction of the current flow relative to the electrode. In general, the polarity of the electrode can be either positive or negative.
Depending on the requirement, some electrode and work metal combination gives better results when the polarity is changed.

1.8.2.8 Frequency

Frequency is a measure of the number of time the current is turned on and off. During roughing, the on time is increased considerably for high removal rates and there are fewer cycles per second, hence a lower frequency setting. Finish cycles will have many cycles per second hence a larger frequency setting.

1.9 ELECTRODE MATERIAL

The tool material generally used can be classified as metallic materials, non-metallic materials and combinations of metallic and non-metallic materials. Metallic materials such as copper, brass and copper-tungsten materials are used and Non-metallic materials such as graphite, copper-graphite are used tool materials in Electric discharge machining process.

1.10 DEVELOPMENT OF MATHEMATICAL MODELS

1.10.1 Response surface methodology

The study of Response Surface Methodology is needed for having an idea how the relations among the process parameters are generated for a particular response parameter (Myers & Montgomery 1995). RSM is a regression technique mainly used for prediction, determination and optimization of machine performances (Masan et al 2003). RSM is a collection of statistical and mathematical technique required for developing, improving and optimizing a process (Khuri & Cornell 1996). Generally, it is used in those circumstances where the output is dependent on many
parameters. The multi parameters related output is called response. RSM involves planning of strategy for development of a relationship between different input parameters and output responses (Myers & Montgomery 1995). The relationship between different process parameters and response is approximately represented by the following general Equation (1.1).

\[ Y = f(\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_k) + \epsilon \]  

- (1.1)

where \( Y \) is the response and \( \varepsilon_1, \varepsilon_2, \ldots, \varepsilon_k \) are the different process parameters, and an additional term correspond to the background noise, error in measurement of response etc., which all together represents the statistical error. The general Equation (2.8) form is written as follows

\[ E(y) = E[ f(\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_k) ] + E(\epsilon) = f(\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_k) \]  

- (1.2)

In terms of coded variables response surface Equation (1.3) can be approximated as follows:

\[ \eta = f(x_1, x_2, \ldots, x_k) \]  

- (1.3)

where \( x_1, x_2, \ldots, x_k \) are coded values. For an approximate value normally a low order polynomial with a small region of independent process variable space is used. The first order RSM model is used when the approximation of response surface is done on a very small region of the independent variable space and there is a little curvature in the response surface (Myers & Montgomery 1995).

The first order model in coded form for two independent variables is given by Equation (1.4)
\[ \eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \]  

- (1.4)

If the interaction is considered between the terms then following Equation (1.5) is obtained:

\[ \eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 \]  

- (1.5)

If addition to the interaction terms introduced there is a curvature in the model which is not adequate to give exact approximation of the model. In such cases second order model is used which is represented by the following Equation (1.6)

\[ \eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \]  

- (1.6)

This model is an exact representation to model the response surface in relatively small surface. The parameters are determined by least square method in second order response equation. The first order response model is represented by the following Equation (1.7)

\[ \eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k \]  

- (1.7)

and the second order response model is represented by the following Equation (1.8) (Myers & Montgomery 1995).

\[ \eta = \beta_0 + \sum_{j=1}^k \beta_j x_j + \sum_{j=1}^k \beta_{jj} x_j^2 + \sum_{j<k} \beta_{jj} x_j x_k \]  

- (1.8)

Generally, a full factorial design would provide estimation of all the necessary parameters (\( \beta \)). The major problem of using the full factorial designs are expensive to use as the number of runs increases rapidly with the number of factors. Therefore, for the analysis Box-Behnken Design is useful
as it help to fit the second order models to the response with the use of a minimum number of experimental runs (Jeff Wu & Hamanda 2002), Montgomery (2003). Generally, Box Behnken Design performs non-sequential experiments. That is, only planning to perform the experiments once. The BBD allows efficient estimation of the first and second–order coefficients. Hence, the BBD have fewer design points; they are less expensive to run than central composite design with same number of input factors. BBD can prove useful in the safe operating zone for the process. Central composite designs normally have axial points outside the "cube" (unless it is specified less than or equal to one). Hence, these points may not be in the region of interest or may be impossible to run because they are beyond safe operating limits. Box-Behnken Designs do not have axial points, thus, it can also be sure that all design points fall within the safe operating zone (Cochran & Cox 1962). BBD ensure that all factors are never set at their high levels simultaneously. In normal practice, two or three centre runs are sufficient in order to get a reasonable estimate of experimental error (Khuri & Cornell 1996).