CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

The literature survey has been carried out to have an overview of the EDM process, modelling of process parameters, influence of process parameters such as input electrical variables, pulse shape, material properties and discharge energy on machining characteristics, controlling the machining process parameters, empirical relationships between process parameters and optimization of process parameters in EDM process. It has helped to know what has already been done in EDM process and what possibilities for extension work have been there.

2.2 STATE OF ART IN EDM PROCESS

Since the electrical discharge machining process involves with non-linear nature, it requires a lot of improvements on it. Many authors have discussed the research possibilities for improving process efficiency of the EDM process. The fundamentals of EDM process mechanism and research works carried out from the inception to the development of the die-sinking EDM process within the past decade have been discussed by Ho and Newman (2003). The researches in EDM process relating to improve the process performance measures, optimizing the process variables, monitoring and controlling of the sparking process have been reported. Norlina Mohd Abbas et al. (2007) presented the recent research trends to improve the performance
characteristics involved in all the aspects of electrical discharge machining process. It has been discussed about the need of controlling the process parameters to enhance the machining process efficiency of the EDM process.

The development of new technologies for improving the surface quality of workpiece is a significant research area in EDM process. Sanjeev Kumar et al. (2009) presented a review on the phenomenon of surface modification by EDM and future trends of its applications. It was observed that most of the research works had focused on surface modification using the powder mixed dielectric medium in EDM process. The study of the impact of the electrical process parameters on surface modification of the workpiece had been taken up by very few researchers. Pham et al. (2004) discussed the recent developments and issues in EDM process in its various forms (diesinking, drilling, wire and milling). It was claimed that the overall machining efficiency had been mostly influenced by electrical process parameters. The complicated relationships between the process parameters and optimization have been mostly formulated with empirical models.

2.3 EFFECT OF PULSE GENERATOR ON EDM PERFORMANCE

Since the electrical energy is supplied to the EDM process in the form of the DC pulses, the pulse generator needs to be upgraded to improve the performance measures in the machining process. The lower energy pulses enhance the surface finish of the workpiece whereas the higher energy pulses improve the material removal rate.

Jahan et al. (2009) conducted a detailed experimental investigation to find out the influence of major operating parameters on surface quality of Tungsten carbide with both transistor and RC-type generators in EDM process. It was proved that RC pulse generator had produced smoother
surface finish than the transistor pulse generator due to its lower discharge
energy distribution over the surface of Tungsten carbide. Fuzhu Han et al.
(2007) developed a modified transistor pulse generator to produce higher
material removal rate than the RC pulse generator in the electrical discharge
machining process. It was found that the transistor pulse generator had
provided two or three times higher machining speed than the conventional RC
pulse generator.

A pulse generator based on fixed pulse width modulation was
developed by Mu-Tian Yan and Yi-Ting Liu (2009) to generate the high
frequency and short duration pulse control signals for reducing surface
roughness in the EDM process. From the experimental results, it was
observed that the very low discharge energy pulse applied between the tool
and the electrode had improved the surface quality of workpiece during the
the development and application of a new power supply in wire electrical
discharge machining process. A transistor-controlled power supply composed
of a low energy discharge circuit was designed to provide the functions of
high frequency and lower energy pulse control. The experimental results
showed that the low peak current resulted in better surface finish in EDM
process. Fuzhu Han et al. (2004) developed a new transistor type pulse
generator with high frequency response to produce higher erosion rate of the
workpiece in the electrical discharge machining process. From the
experimental results, it was observed that the modified transistor pulse
generator had produced 24 times higher material removal rate than the RC
pulse generator in the EDM process. Mu-Tian Yan and Yi-Peng Lai (2007)
presented the development of a fine-finish power supply with high frequency
in EDM process. This power supply had been composed with full bridge
circuit, two snubber circuits and a pulse control circuit. It was found that the
proposed power supply had produced lower discharge energy and thus
contributed to lower surface roughness. An attempt was made to establish a new EDM impulse generator based on high frequency switched DC to DC series-parallel resonant converter by Rosario et al. (2004). It was claimed that the capacitance effect had affected the overall impedance of the EDM arrangement and thus altered the machining characteristics of EDM process.

2.4 FACTORS AFFECTING THE EDM RESPONSE PARAMETERS

The effects of various factors such as pulse shape, electrical process parameters, discharge energy and tool material properties on performance measures of the EDM process are discussed in this section with the light of earlier research findings.

2.4.1 Influence of Pulse Shape on Machining Characteristics

Studying the variation of the EDM process response characteristics due to change in shape of the generated pulse is one of the research aspects in the EDM process. The effects of the voltage excitation of the pre-ignition spark pulse on the performance measures such as material removal rate, electrode wear rate and average surface roughness were discussed by Ghoreishi and Tabari (2007). Based on the results, it has been cleared that applying voltage excitation to the pulse has produced an effective pulse which in turn increased material erosion and surface quality. The influence of the current impulse on machining Tungsten carbide and SKD die steel with electrolytic Copper tool electrode in the EDM process was investigated by Tsai and Lu(2007). From the experimental results, it was found that the material removal rate and tool wear rate (TWR) had been affected by the energy density.
Seong-Min Son et al. (2007) investigated the influences of electrical pulse condition on the machining characteristics in the EDM process. It was found that the duration of pulse considerably affected the machining characteristics such as material removal rate, tool wear rate and surface accuracy. It was also realized that the shorter EDM pulse could be efficient to make a precision part. Liu et al. (2009) described the influence of the EDM discharge pulse shape on the machining characteristics such as material removal mechanism of Si$_3$N$_4$ – TiN. The surface texture of machined workpiece had been investigated with different form of discharge pulse such as relaxation and iso current pulse. It was proved that uniform discharge energy had produced good surface topography. Janardhan and Samuel (2010) analyzed the effect of machining parameters on material removal rate and average surface roughness using the pulse train data acquired at the spark gap with the help of MATLAB software package. It was observed that the material erosion rate had been increased with decrease in the pulse off time in EDM process. A new pulse discriminating technique was proposed by Yeo et al. (2009) for monitoring electrical discharge machining process. This system had employed the current pulse as the main detecting parameter as it was considered to be a better representation of the spark energy inside the plasma channel in comparison with the voltage. This system was able to classify discharge pulses into normal discharge, delayed discharge, arcing and short circuit accurately.

2.4.2 Influence of Process Parameters on Machining Characteristics

Many research works have been conducted to find the influence of process parameters especially electrical process parameters on EDM process. Most of the research works reveal that the discharge current and machining time has the most influencing nature on the EDM performance measures. Gostimirovic et al. (2012) investigated the effects of electrical process
parameters on the performances of die-sinking electrical discharge machining process. It was found that the discharge current and pulse duration had highly influenced the material removal rate of the EDM process. Mohan et al. (2002) analyzed the effect of EDM process parameters such as electrode material, polarity, pulse duration, current and rotation of the electrode on the material removal rate, tool wear rate and surface roughness. It was found that the material removal rate and tool wear rate increased with the discharge current during machining process. Mohan et al. (2004) investigated the surface roughness of the SiC/6025Al composite surface using electrical discharge machining process with Brass as the tubular electrode. From the experimental results, it was observed that increasing peak current had resulted in higher surface roughness during the machining process.

Seo et al. (2006) discussed the drilling process of a functionally graded 15-35 volume% of silicon carbide particulate reinforced Al359 metal matrix composite by electrical discharge machining process to assess the machinability and workpiece quality. It was observed that the peak current and pulse on time had increased the material removal rate. It had also been reported that increase in percentage SiC particles had decreased the material removal rate and electrode wear rate. Puertas et al. (2004) carried out a study on the influence of the factors of current intensity, pulse time and duty cycle over the material removal rate, surface quality and electrode wear rate. A relationship model between the input parameters and response parameters in the die-sinking EDM process using response surface methodology was developed. It was concluded that the lower values of the current intensity and the machining time had to be used in order to obtain a good surface finish. The use of the dimensional analysis for investigating the effects of the electrical and the physical parameters on the material removal rate of die-sinking EDM process was described by Yahya and Manning (2004). From the
experimental results, it was found that the material removal rate had been increased with discharge current, gap voltage and pulse on time.

Huang et al. (1999) made an attempt to unveil the influence of the process parameters on the machining SKD11 alloy steel using EDM process. It was found that the pulse on time and spark gap had the most significant nature to affect the performance measure such as surface roughness and white layer depth using numerical analysis. Mathematical models relating process parameters and performance measures have been established by regression analysis. Kuppan et al. (2008) reported about the experimental investigation of small deep hole drilling of Inconel 718 with electrolytic Copper tool electrode using the electrical discharge machining process. The experimental results showed that the material removal rate had been increased with the increase in the peak current and duty factor. Patel et al. (2008) investigated the feasibility of fabricating micro holes in SiCₚ – Al composites using electrical discharge machining with a rotary tube electrode. The experiments were carried out with the material removal rate, electrode wear rate and hole tapper as the response variables in the study. The experimental results revealed that pulse on duration had significantly affected the response characteristics involved in EDM process. A set of designed experiments with varying process parameters such as pulse current, open circuit voltage and pulse duration were carried out by Pelicer et al. (2009) to study the effect of triangular, cylindrical and rectangular shaped Copper electrodes on machining H13 steel. It was concluded that the triangular shaped electrode had produced highly inefficient surface profile, due to the fast wearing nature of the electrode edges. Wang et al. (2011) carried out a series of experiments to investigate the impacts of machining polarity, electrode rotation speed and nominal capacitance on the material removal rate and tool wear rate with poly crystalline diamond. During the plasma formation, more electrons impinge with positively charged workpiece and which leads to higher material removal
rate. It was demonstrated that favorable machining performance of EDM process on the workpiece could be achieved in tool with negative polarity as compared to the positive polarity.

Nihat Tosun et al. (2004) presented an investigation into the effect and optimization of machining parameters on kerf and material removal rate in wire EDM process with Taguchi method. The experimental studies were conducted under varying pulse duration, gap voltage, wire speed and flushing pressure with AISI 4140 steel as workpiece material. Based on the ANOVA method, the high effective parameter on both kerf and material removal rate was found as pulse duration. Renjie Ji et al. (2011) presented a new process of machining SiC ceramics using electrical discharge milling process. The effects of tool polarity, pulse duration, voltage and peak current on the process performances such as material removal rate, electrode wear rate and surface roughness were investigated. It was found that the negative polarity tool electrode with longer pulse duration had produced high material removal rate and surface roughness. Rebello et al. (2000) presented an experimental study on the effect of electric discharge machining parameters on material removal rate and surface quality with high strength Copper – beryllium alloys. It was found that the plasma diameter had been decreased with pulse duration and discharge current during the machining process.

Po-Huai Yu et al. (2011) examined the use of electrical discharge machining on machining poly-crystalline silicon. The effects of different WEDM process parameters on machining characteristics were explored. From the experimental results, it was indicated that the pulse on time had a great influence on the cutting speed in Wire EDM process. Ajay Batishe et al. (2012) investigated the effect of process parameters and mechanism of material deposition in electric discharge machining on surface properties of EN31, H11 and high carbon high chromium die steel materials. The material transfer
mechanism involved in EDM process has been discussed. It has been found that die steels have been machined effectively with Copper tool electrode using EDM process. Patel et al. (2009) presented a detailed experimental investigation of machining characteristics such as surface integrity and material removal mechanisms of advanced ceramic composite Al₂O₃ – SiC₆ - T₇C with EDM process. The surfaces were assessed and characterized using scanning electron microscope. It was concluded that the surface roughness and material removal rate had been increased with pulse duration in EDM process.

2.4.3 Influence of Discharge Energy on Machining Characteristics

In view of the fact that the discharge energy is converted into the thermal energy to melt and vaporize the material in EDM process, it becomes imperative to discuss the influence of the pulse energy on the machining characteristics in such process. Jahan et al. (2009) conducted an experimental investigation with a view to obtain fine surface finish in die-sinking EDM process of Tungsten carbide using different tool electrodes such as Tungsten, Copper Tungsten and silver Tungsten. It was found that the surface finish had been influenced by the discharge energy during machining process. It was realized that the lower discharge energy had produced good surface finish. Swee Hock Yeo et al. (2009) discussed the machining of zirconium based bulk metallic glass by EDM process with different tool electrodes such as Copper, Brass and Tungsten rod electrode. The experimental results showed that the usage of lower input energy had produced the lower surface roughness and electrode tool wear. Asit Kumar Khanra et al. (2007) investigated the influence of energy input on the workpiece surface during the machining in the EDM process. In this experimental investigation, a well-polished mild steel (C- 0.18%) plate had been used for machining by EDM. It
was observed that the energy input had influenced the debris particle size in the EDM process.

Marcel Sapin Popa et al. (2009) showed the importance of optimizing the process parameters that could influence the quality of the EDM process. An equation of crater depth was formulated in terms of discharge energy of EDM process. From the relation, it was observed that the crater depth had been increased with the discharge current flowing through the workpiece and tool electrode. Kojima et al. (2008) described the spectroscopic measurement of arc plasma diameter in EDM. It was found that the arc plasma had been increased with increasing discharge current. A decrease in crater diameter and depth with increasing gap width was observed due to the increased plasma diameter. The arc plasma diameter had increased with increasing spark gap and thus clarified the reason for lower material removal rate and smoother surface finish with longer spark gap. Wong et al. (2003) developed a single spark pulse generator using resistance – capacitance arrangement to study the erosion characteristics in the EDM process from the crater size. The volume and the size of the craters were found to be more consistent at lower energy discharge sparks than at the higher energy discharge sparks.

The higher energy pulse leads to the micro surface crack on the work surface. Yan-Cherng Lin et al. (2008) investigated the machining of Tungsten carbide graded K10 and P10 by electrical discharge machining using an electrolytic Copper electrode. The input machining parameters of EDM process were varied to explore the effects of electrical discharge energy on the machining characteristics such as material removal rate, electrode wear rate and surface roughness. It was realized that the material removal rate and electrode wear rate increased with the density of the electrical discharge energy. Serious surface cracks were reported with high level electrical
discharge energy. Muslim mahardika et al. (2008) presented a fundamental study of the total energy of discharge pulses required to machine different workpiece materials. In contrast to \( \lambda, \theta \) theory, the \( \lambda, \theta, \rho \) theory has been proposed; because lower resistivity results in better transfer of the discharge current, where \( \rho \) is the electrical resistivity of the material, \( \lambda \) is the thermal conductivity and \( \theta \) is the melting point of workpiece material. Guu et al. (2007) aimed to investigate the machining characteristics of manganese-Zinc ferrite magnetic materials using electrical discharge machining process. The experimental results indicated that the morphology of debris revealed the mechanism of material removal. It was observed that a better machined surface had been obtained by setting process parameters at low pulse energy level. The theoretical modelling of the EDM process based upon the heat transfer equations was established by Harminder singh(2012). In the study, the input energy equation was developed as a function of pulse duration, current, polarity of electrode and properties of the workpiece and tool electrodes. This model is helpful to calculate the optimal process parameters for obtaining optimum discharge energy.

### 2.4.4 Influence of Material Properties on Machining Characteristics

The material properties of tool electrode and work piece such as electrical conductivity, boiling point, melting point and hardness may affect the electrical machining process. Jose Duarte Marafona and Arlindo Araujo (2009) showed the influence of the hardness of the workpiece on the material removal rate and average surface roughness with various alloy steels using the EDM process. A linear regression model was developed for material removal rate using the hardness of the workpiece and its interactions in EDM process. Jercy Kozak et al. (2004) proved that the change in resistance had caused change in material removal rate and surface roughness of the EDM product. In the study, the change in resistance offered by various workpiece was taken
into account. It was found that the silver coated workpiece had produced higher material erosion. Nakaoku et al. (2007) conducted an experimental research on the machining of sintered diamond by EDM process. It was understood that the roundness of the machined hole was poor with the surface of large diamond particles sintered diamond in EDM process.

Somashekar et al. (2010) presented the investigation and optimization of various process parameters for the selection of the optimal control setting on micro wire EDM process. It was claimed that the melting point and the boiling point of materials had a significant effect on the process performances in EDM process. It was inferred that the level of discharge energy played an important role on the performance characteristics in EDM process. It was also concluded that lower discharge energy had produced a more accurate surface. Tahsin Tecelli Opuz et al. (2009) experimentally investigated the shape and dimensional geometry of blind micro holes produced by EDM process using Tungsten carbide tool electrode. It was found that the electrical discharges could occur as arcs rather than sparks due to parasitic reactance. From the experimental results, it was realized that the less pulse duration had resulted in less tool wear due to lower electric discharge intensity.

2.4.5 Influence of Process Parameters on Surface Topography

The variation in the craters formed by EDM process affects the surface topography of the machined surface. Liao et al. (2004) modified the traditional RC pulse supply circuit with the low energy for ignition in order to obtain lower surface roughness using electrical discharge machining process. The experimental results showed that the modified lower energy pulse generating circuit had produced tiny crater depth over the workpiece surface to achieve good surface finish. Abdul Kareem et al. (2011) investigated the effect of electrical discharge machining variables on surface topography of
stainless steel. An increase in pulse current had resulted in the poor surface integrity of the workpiece during the machining process in EDM.

Ahmet Hasiclik and Ulas Caydas (2007) evaluated the quality of an EDM product in terms of surface roughness. The machining of Titanium alloy (Ti–6Al–4V) using EDM process was carried out with different electrode materials namely, graphite, electrolytic Copper and aluminium and process parameters such as pulse current and pulse duration. From the experimental results, it was concluded that crater size had a pronounced effect on the surface roughness. Kiyak and Cakir (2007) studied the influences of the EDM process parameters on surface roughness for machining AISI P20 steel, which has been used in the production of plastic mold and die. It was observed that the surface roughness of the workpiece and the tool electrode were influenced by the pulse current and pulse duration. The higher values of these parameters had increased the surface roughness of the workpiece.

Lauwers et al. (2004) presented a detailed experimental investigation of the material removal mechanisms of some commercially available electrical conductive ceramic materials (ZrO₂-TiN, Si₃N₄-TiN, Al₂O₃-SiC-TiC) through analysis of debris and surface quality. It was found that the irregular crater pattern had increased the surface roughness of machined surface using EDM process.

Patowari et al. (2011) made an attempt to modify the surface integrity of C-40 steel in EDM process with WC-Cu powder metallurgy green impact tools. Tungsten carbide was used as the tool because of its ability to produce a hard layer over the work surface. It was concluded that lower current setting at lower duration had resulted in smoother surface in EDM process. Sanjeev Kumar and Uma Batra (2012) investigated the surface modification by electric discharge machining of three different die steels with Tungsten powder mixed dielectric medium. It was found that the favourable
response characteristics had been obtained at low discharge current, shortest pulse duration and negative polarity of the tool electrode.

2.4.6 Effect of Process Parameters on Tool Wear

The reduction in the tool wear is preferable in any machining process. Ali Ozgedik and Can Cogun (2006) investigated the effects of machining parameters on performance measures involved in EDM process. The workpiece material 1040 steel was machined with various pulse duration, discharge current and flushing pressure. It was experimentally found that increasing discharge current in the machining process would increase the material removal rate, tool wear rate and surface roughness. Suleiman Abdul Kareem et al. (2010) reported the study of the electrode cooling effect during the machining process of Titanium alloy (Ti-6Al-4V) using EDM process. From the experimental results, 27% of electrode wear was observed during the EDM process of Titanium alloy with electrodes cooled by liquid nitrogen compared to the EDM process of the same material without cooling of the tool electrode. Vineet Srivastwa and Pulak Pandey (2012) conducted a study on the cooling effect on Copper electrode during electrical discharge machining of M2 grade high speed steel workpiece. Electrode wear rate and surface roughness were observed to evaluate the machinability of the workpiece with Copper tool electrode. From the experimental results it was inferred that lower pulse duration and discharge current maintained the higher surface finish of the workpiece.

2.5 MONITORING AND CONTROL OF THE EDM PROCESS

The EDM process parameters have to be monitored during the machining process, so that the controlling of those parameters can be done to obtain the required response parameters. The main action of monitoring and controlling the process is to observe and measure process parameters to
reduce the deviation of performance measures from the expected level. An adaptive control system for process monitoring, identification and control in the wire electrical discharge machining process was developed by Mu-Tian Yan (2010). It was realized that the wire breaking could be controlled by the adjustment of pulse interval of each pulse cycle of supply. Ulas caydas et al. (2009) developed an adaptive neuro- fuzzy inference system model for the prediction of the surface roughness of machined surface using wire EDM process as a function of process parameters such as open circuit voltage, pulse duration and wire feed rate. From the experimental results, it was found that the proposed control system had improved the surface quality in EDM process.

Oguzhan Yilmaz et al. (2006) introduced a user friendly intelligent system based on the knowledge of the skilled operators for the selection of the EDM process parameters for machining AISI 4340 stainless steel. The system was provided with a compact selection tool based on expert rules and enabled an unskilled user to select necessary parameters which lead to lower electrode wear rate and better surface quality. Ming Zhou and Fuzhu Han (2009) developed an adaptive control system which directly and automatically regulated the tool down time for improving the process performance in EDM process. It was observed that this adaptive system would improve the machining rate, due to the automatic adjustment of spark gap. Mu-Tian Yan and Hsing-Tsung Chien (2007) developed a new pulse discriminating and control system for process monitoring in EDM process. The effect of pulse interval, machining feed rate and workpiece on the variation of the proportion of normal spark, arc and short circuit in the total spark was studied. The experimental results have indicated that the developed control system had significantly reduced the arc discharge in EDM process to achieve stable machining.
Yih-Fang Chang (2005) designed a proportional derivative controller of the spark gap between an electrode and a workpiece to analyze the non-linearity involved in EDM process. It was concluded that this non-linearity reduced the effective discharge in electrical discharge machining process. Behrens and Ginzelt (2003) proposed a neuro-fuzzy based gap width controller for a highly efficient removal mechanism in EDM process. The experimental results indicated that the proposed controller enhanced EDM process to achieve the better surface finish of workpiece. Kao and Albert Shih (2008) monitored the discharge current in electrical discharge machining using high speed data acquisition with high frequency response. From the experimental results, it was found that decrease in air gap between tool and workpiece improved the material removal rate in EDM process.

Hao Tong et al. (2008) designed an experimental system with a macro/micro dual feed spindle to improve the machining performance of servo scanning micro EDM process, which utilized an ultrasonic linear motor as the macro drive and a piezoelectric actuator as micro feeding mechanism. Based on LabVIEW software package, a real time control system was developed to control coordinately the dual-feed spindle to drive the tool electrode. Cao Fenggou and Yang Dayong (2004) presented a method to automatically determine and optimize the process parameters on the EDM sinking process with the application of artificial neural network. The experimental results proved that automatic determination of current value would be an efficient method for improving EDM performance.

2.6 MODELLING OF EDM PROCESS PARAMETERS

The process parameters modelling help to analyze the influence process parameters on the machining characteristics in any of the machining processes. This section discusses about the mathematical modelling of process parameters and simulation models in the EDM process.
2.6.1 Theoretical Modelling of Process Parameters

Since the two electrical conductors such as tool electrode and workpiece are separated by a dielectric medium, the EDM arrangement can be modeled as a capacitor. Shuyang Liu et al. (2011) constructed a plate capacitor model for electrical discharge machining process. The correlation actions of process parameters and energy distribution were discussed based on the field electron emission theory. It was observed that machining time played a major role to improve the process efficiency. Saradindu Das and Suhas Joshi (2010) developed a comprehensive mathematical model to predict the spark erosion rate involved in EDM process. It was found that the plasma current and plasma radius had been increased with pulse duration. It was proved that the erosion rate of workpiece had been increased gradually with pulse on time. Owing to its direct dependence on the plasma current, a lot of fluctuations of the erosion were seen at longer pulse duration.

Owing to the importance of the thermal energy in the EDM process, it is important to develop thermal based process parameters model. Salonitis et al. (2009) developed the thermal based model for the determination of the material removal rate and average surface roughness achieved as a function of the process parameters in the EDM process. It was estimated that the increase in discharge current during the machining process with EDM resulted in the formation of higher material erosion rate and the coarse surface crater on the workpiece surface. Deepak Panda and Rajat Kumar Bhoi (2006) proposed a three dimensional transient heat conduction model where the growth of the plasma channel had determined the machining characteristics in EDM process. A temperature distribution function to compute the depth of the crater and surface roughness was developed. The experimental and theoretical results showed a the significant similarity
between them. Katz and Tibbles (2005) proposed a micro EDM model along with numerical simulation and experimental validation. The thermal modeling of the EDM process was created by the heat diffusion equation. The experimental results have proved that the size of the electrode had influenced the discharge process on the workpiece due to the change in the electric field intensity.

Izquierdo et al. (2009) presented an original numerical model for simulating the machined surface using the electrical discharge machining process. This model generated electric discharge machined surfaces by calculating temperature fields inside the workpiece using a finite difference based approach. The characteristics of the discharge for a given operation, namely energy transferred onto the workpiece, diameter of the discharge channel and material removal efficiency could be estimated using inverse identification from the results of the numerical model. Kansal et al. (2008) developed an axisymmetric two-dimensional model for powder mixed EDM process using finite element method. This model utilized the several important aspects such as temperature sensitive material properties, shape and size of the heat source, pulse duration percentage distribution of heat energy among tool, workpiece and dielectric fluid to predict the material removal mechanism in powder mixed EDM process.

Some researchers developed the neural and fuzzy based models considering EDM arrangement as a heat source. Yeo et al. (2008) analyzed the five different EDM models in terms of temperature distribution, crater geometry and material removal rate. From the experimental validation, it was concluded that the heat source models could be enhanced by improving the approximation of the heat flux and energy fraction. From the heat source models, the response characteristics such as material removal rate and crater depth were estimated. Kuo-Ming Tsai and Pei-Jen Wang (2001) established
six neural models and a neuro-fuzzy model for material removal rate in EDM process and analyzed the machining process parameters using petrinet technique. From the experimental analysis, it was concluded that the material removal rate in EDM process including change of the tool polarity could be predicted with reasonable accuracy with ANFIS (Adaptive Network based Fuzzy interference System) model.

2.6.2 Empirical Models of EDM Process Parameters

The complex interactions between various EDM process parameters lead to develop the empirical models of process parameters. These models have been formulated based on the responses obtained with different settings of process parameters to analyze the machining process. Yih-Fong Tzeng and Fu-Chen Chen et al. (2003) presented a simple approach based on Taguchi robust design for optimizing the process parameters of electric discharge machining. It was noted that the surface roughness of the machined workpiece should be taken into account in the methodology to improve the surface quality. Srinivasa Rao et al. (2010) developed the mathematical model for predicting material removal rate, tool wear rate and surface roughness in die-sinking EDM process with AISI 304 stainless steel using fuzzy logic approach. It was found that the accuracy of the prediction of the performance measures in EDM process could be improved by the number of experiments conducted. Joshi and Pande (2011) developed a unique integrated approach for modelling and optimization of the EDM process using Finite Element Methodology, Artificial Neural Network and Genetic algorithm. This approach provided flexibility to the user for choosing the optimum parameters of specific applications. Kalpakjian (1997) formulated the models for material removal rate and surface roughness in terms of the EDM process parameters.

Ulas Caydas and Ahmet Hascalik (2008) made an attempt to model the electrode wear in electrical discharge machining using response surface
methodology. It was found that the pulse current had a significant effect on the electrode wear during the machining process. Hewidy et al. (2005) developed the mathematical models for correlating the inter-relationships of various EDM machining parameters such as peak current, duty factor and dielectric pressure on material removal rate, surface roughness and wear ratio with Inconel 601 material. These models were formulated based on the response surface methodology.

Sarkar et al. (2008) developed a second order mathematical model in terms of machining parameters for surface roughness and cutting speed using response surface methodology. It was proved that the surface quality of the workpiece decreased during higher cutting speed in wire EDM process. Sushant Dhar et al. (2007) evaluated the effect of current, pulse on time and gap voltage on material removal rate, tool wear rate and radial overcut on electrical discharge machining of Al-4Cu-6Si alloy with 10 weight percentage of SiC<sub>p</sub> composites. A second order non-linear mathematical model was developed for establishing the relationship among the EDM process parameters. Assarzadeh and Ghoreishi (2008) presented a new integrated neural network based approach for the prediction and optimal selection of process parameters in die-sinking electric discharge machining with a flat electrode. It was inferred that the neural model could predict the process performances of the EDM process with reasonable accuracy under many machining conditions. Esme et al. (2009) established a mathematical relation between surface roughness and electrical input process parameters using regression analysis in the wire EDM process. It was observed that the increasing the pulse duration during the machining process had resulted in better surface roughness of the workpiece. Kuo-Ming Tsai and Pei-Jen Wang (2001) illustrated the comparisons on predictions of surface finish for various work materials with the change of electrode polarity based upon six different neural network models and neuro-fuzzy network model. A semi-empirical
model of average surface roughness in terms of thermal properties of work materials was presented with neural-network model.

### 2.6.3 Simulation Models of EDM Process Mechanism

The simulation model of any process is helpful to predict the performance measures during the actual process. Sanchez et al. (2009) presented a computer simulation model of the EDM process based on the numerical calculation of temperature field within the workpiece, from which the amount of material removal could be estimated. From the experimental results, it was found that the surface roughness could be determined by plasma radius. Segon Heo et al. (2009) proposed a three dimensional geometric simulation method of the EDM milling process with Z-map algorithm. This simulation model was used for predicting optimal process parameters of actual machining such as electrical conditions in the EDM milling process.

The determination of the discharge locations and spark energy based on the process parameters and material properties is a challenging field in the EDM process. The development of a die-sinking EDM simulation method by determining discharge locations on discharge delay time has been discussed by Kenji Morimoto and Masanori Kunieda (2009). The discharge delay time of the every voxel has been calculated probabilistically based on the parameters such as machining are, gap width and debris diameter. The discharge location has been determined with the voxel with minimum discharge delay. Ding et al. (2002) introduced a computer aided electrode design system for the die and mold manufacturing. From the experimental validation, it was proved that this system could automatically suggest the electrode tool, its holder and a work co-ordinate system for obtaining efficient EDM process based on the selection of the electrode boundaries. Young Hun Jeong and Byung-Kwon min (2007) developed a geometric simulation model
of the EDM drilling process with cylindrical tool to predict the geometry of
the drilled hole using the EDM machining process. It was claimed that the
crater volume had been influenced by the spark energy in the EDM process.
Yongshun Zhao et al. (2004) developed a geometric model for the linear
motor equipped EDM die-sinking process based on the Z-map method. This
model was employed to calculate the minimum gap distance for the discharge
sparks to occur between the workpiece and the tool electrode. The influence
of the peak current and discharge duration on the average surface roughness
was simulated using the model.

2.7 OPTIMIZATION OF EDM PROCESS PARAMETERS

Optimization techniques are used to select the input parameters for
obtaining maximum or minimum level of response. Jose Marafona and
Catherine Wykes (2000) described an investigation into the optimization of
material removal rate in the electric discharge machining process with Copper
Tungsten tool electrode. From the experimental results, it was concluded that
large current intensity would result in higher material removal rate. Matoorian
et al.. (2008) presented the application of the Taguchi robust design methods
to optimize the precision and accuracy of the EDM process for the machining
of precise cylindrical forms on hard and difficult-to-machine materials. It was
found that the current intensity of the EDM process affected the material
removal rate greatly. The relationship between material removal rate with the
input process parameters was formulated using regression equation.

Multi response optimization is helpful to obtain the optimum input
process parameters for achieving multiple favorable responses. Noorul Haq
et al. (2008) presented a new approach for the optimization of the drilling
parameters on drilling Al/SiC metal matrix composites with multiple
responses based on the orthogonal array with Grey relational analysis.
Experimental results showed that the responses in drilling process could be
improved effectively through the proposed approach. Siddhi Jailani et al. (2009) made an attempt to optimize the sintering process parameters of Al-Si alloy with fly ash composite using Grey relational analysis. From the experimental results, it was observed that the multiple response characteristics of sintering process parameters could be improved by 1.9% effectively through Taguchi – Grey relational analysis.

Yih-Fong Tzeng and Fu-Chen Chen (2007) described the application of the fuzzy logic analysis coupled with Taguchi methods to optimize the precision and accuracy of the high speed electrical discharge machining process. The most important factors affecting the precision and accuracy of the high speed EDM process were identified as duty cycle and peak current. Shajan KuriaMale and Shunmugam (2005) developed a multiple regression model to represent the relationship between the input and output process variables. The multi objective optimization method based on non-dominated sorting genetic algorithm to optimize the EDM process parameters was carried out in the study. Hsien-Ching Chen et al. (2010) proposed a method integrating back propagation neural network and simulated annealing algorithm to determine optimal parameter setting of wire EDM process for average surface roughness. It was claimed that the pulse duration had the most significant role on determining surface integrity. Lin et al. (2000) reported about the Taguchi method with fuzzy logic approach for optimizing the electrical discharge machining process with multiple performance characteristics. It was concluded that the performance characteristics such as electrode wear rate and material removal rate could be improved through this approach. Seung-Han Yang et al. (2009) presented a constrained multi objective optimization methodology for EDM process using simulated annealing approach. This system model was employed to simultaneously maximize the material removal rate as well as minimize the surface roughness using simulated annealing scheme.
It has been observed that Grey relational analysis can improve the response prediction level. Vijay Kumar Meena and Man Singh Azad (2012) performed micro electric discharge machining of Ti-6Al-4V alloy with Tungsten carbide. The researchers performed Taguchi-Grey relational analysis to optimize the input process parameters such as current, voltage, frequency and gap width for obtaining the multiple performance characteristics. It was proved that the proposed optimization technique had improved the response parameters in terms of material removal rate and tool wear rate. Jong Hyuk Jung and Won Tae Kwon (2010) used the Grey relational analysis theory to resolve the complicated interrelationships among the multiple response characteristics in EDM process. It was found that the electrical process parameters had the most significant controlling nature in EDM process.

2.8 GAPS IDENTIFIED IN THE RESEARCH AREAS OF EDM PROCESS

Even though many research works were carried out to study the influence of process parameters on machining characteristics in EDM process, only a small amount of literatures is available to enhance the process parameters to improve the machining efficiency. It is learnt that only a few studies relating to electrical pulse parameters have been conducted. Very little attention has been paid to control the pulse shape for enhancing the machining characteristics and to reduce the arcing effect in EDM process. The influence of tool electrode properties on performance measures of EDM process has been reported in only a few studies. Hence the present investigation has been carried out.