CHAPTER 2

REVIEW OF RELATED LITERATURE

2.1 INTRODUCTION

The study of metal cutting focuses on the features of the behaviour of tool and work materials that influence the efficiency and quality of cutting operations. Development of cutting tool materials has held a key position. One of the current challenges faced by manufacturing industries is the reduction of process time and improvement of performance through optimization of controllable process parameters using different optimization techniques. This can be obtained by experimentation or using any model developed from the experiment. Although performance improvement in EDM has been studied extensively, proper selection of machining parameters for the best process performance is still a challenging job.

The history of EDM techniques goes as back as the 1770s when an English Scientist invented it. In 1970s, commercially developed wire EDM began to be a viable technique that helped shape the metal working industry, what we are see today. In the mid 1980s, the electrical discharge machine techniques were transferred to a machine tool. This migration made EDM more widely available and appealing over traditional machining processes.

EDM has been replacing drilling, milling, grinding and other traditional machining operations and is now a well-established machining option in many manufacturing industries throughout the world. It is capable of
machining geometrically-complex or hard material components that are precise and difficult-to-machine such as heat treated tool steels, composites, super alloys, ceramics, carbides, heat resistant steels etc. which are widely used in die and mould making industries, aerospace, aeronautics and nuclear industries.

WEDM is considered as a unique adoption of the conventional EDM process, which uses an electrode to initialize the sparking process. However, WEDM utilizes a continuously travelling wire electrode made of thin copper, brass or tungsten of diameter 0.05-0.30 mm, which is capable of achieving very small corner radii. The wire is kept in tension using a mechanical tensioning device reducing the tendency of producing inaccurate parts. During the WEDM process, the material is eroded ahead of the wire and there is no direct contact between the work piece and the wire eliminating the mechanical stresses during machining.

In the literature review, different research articles published in different journals are reviewed and a complete survey has been made to study the various works carried out by the research scholars in EDM and WEDM. Various research papers concentrate mainly on the effect of process parameters on the responses. Some of the research papers dealt with different type of work piece materials. In some of the research publications different techniques like Response Surface Methodology (RSM), Taguchi’s method, artificial neural network, Fuzzy logic, Finite element methods, genetic algorithm and simulated annealing were dealt with to optimize the process parameters.

In this chapter, complete literature survey has been made in both EDM and WEDM by classifying the journal under articles following different aspects:
• Work piece materials
• Process parameters and responses
• Methodology and
• Scanning Electron Microscope (SEM analysis)

2.2 STUDIES ON EDM

The important concern in the EDM process is the optimization of the process parameters such as pulse current intensity ($I_p$), pulse duration ($T_{on}$), pulse off time ($T_{off}$), open circuit voltage ($V$), dielectric fluid types and flow rate to maximize the material removal rate and minimize the surface roughness and the tool wear.

Simultaneously, improving material removal rate and surface finish is another area of research in EDM. Many attempts has been made by different research scholars to optimize the EDM process by conducting experiments with different work piece material, electrode material and combination of process parameters. Optimization of the process performance to improve the surface quality and material removal rate are still challenging problems.

2.2.1 Studies on Workpiece Material

Amorim (2005) conducted experimental investigation on the EDM of the AISI P20 tool steel. The material removal rate, volumetric relative wear of electrode and work piece surface texture Ra which are representative of EDM performance aspects were analyzed against the variation of some of the most important EDM electrical variables like open circuit voltage, discharge duration, pulse interval time and discharge current using copper tool electrodes.
Che Haron et al (2001) conducted experiments on EDM with work piece material of AISI 1045 tool steel using copper electrode of different diameters (9.5, 12 and 20 mm) with the objective of determining possible correlation between EDM machining parameter (current) and machinability factors (material removal rate and electrode wear rate). It was found that the material removal rate as well as the electrode wear rate was not only dependent on the electrode, but also had close relation with the supply of current. Low current was found suitable for small electrode, while high current for big diameter electrode.

Abdulkareen et al (2010) studied the effect of electrode cooling on electrode wear for the EDM of titanium alloy (Ti-6Al-4V). Pulse current, pulse on time, pulse off time, and gap voltage were considered as the machining parameters while electrode wear was the response. Analysis of the influence of electrode cooling on the response was carried out and it was possible to reduce EW by 27% using this method.

Kiyak (2007) conducted experiments on EDM of 40CrMnNiMo864 tool steel (AISI P20) which was widely used in the production of plastic mould and die. Pulsed current (8, 16 and 24 A), pulse time (2, 3, 4, 6, 12, 24, 48 and 100μs) and pulse pause time (2 and 3μs) were selected as EDM process parameters and their effect on the electrode wear and surface roughness of the work piece were studied. Low current and pulse time with high pulse pause time produced minimum surface roughness yielding good surface finish quality. High pulsed current and pulse time provided low surface finish quality. However, this combination would increase material removal rate and reduce machining cost. As a result, this combination (high pulsed current and pulse time) should be used for rough machining step of EDM process. It was emphasized that for rough machining high pulse current
and high pulse time were preferable and low current and low pulse time were preferable for finishing process.

Luis et al (2005) conducted study on the die-sinking EDM of Siliconised or reaction-bonded Silicon Carbide (SiSiC), a conductive ceramic which has a wide range of applications in the industrial field such as high-temperature gas turbines, bearings, seals and lining of industrial furnaces. Intensity supplied by the generator of the EDM machine \(I\), pulse time \(ti\), duty cycle \(\eta\), open-circuit voltage \(U\) and dielectric flushing pressure \(P\) were considered as process parameters and their influence on the material removal rate and electrode wear were analysed using the technique of Design Of Experiments (DOE). In the case of flushing pressure, it was verified that an increase in the flushing pressure 20-60kPa resulted in a decrease in the wear on the electrode.

Shankar Singh et al (2004) investigated the effects of machining parameter such as pulsed current on material removal rate, diametral overcut, electrode wear, and surface roughness for EDM of EN 31 tool steel (IS designation: T105 Cr1 Mn 60) hardened and tempered to 55 HRC. Experiments were carried out by varying the pulsed current with different electrode materials like copper, copper tungsten, brass and aluminum. Copper was comparatively a better electrode material as it gives better surface finish, low diametral overcut, high MRR and low electrode wear.

Mahardika et al (2008) compared physical properties of the titanium alloy Ti-6AI-4V, NAK80 steel and copper. Ti-6AI-4V has a high specific heat, higher melting point and electrical resistivity, which requires more energy during the heating process to melt or vaporize the Ti-6AI-4V material.
Jaharah et al (2008) investigated the machining performance such as surface roughness, electrode wear rate and material removal rate with copper electrode and with work piece of AISI H3 tool steel. Process parameters taken are pulse current, pulse on time and pulse off time. It was concluded that the pulse current was the major factor on material removal rate and surface roughness.

Narcis et al (2011) studied the influence of process parameters on surface quality in EDM of AISI H13 steel. It was found that metal removal rate and surface roughness were increasing with increase of discharge current. Pulse-off variation affected metal removal rate, but its behaviour was not linear due to the interactions with other parameters like voltage, current etc.

Kuppan et al (2008) derived mathematical model for material removal rate and average surface roughness of deep hole drilling of Inconel 718. The experiments were planned using central composite design matrix and response surface methodology was used to model the same.

It revealed that material removal rate was more influenced by the peak current, duty factor and process parameters were optimized for maximum material removal rate with the desired surface roughness value using desirability function approach.

Lin et al (2006) investigated the effects of EDM parameters on machining characteristics MRR, EWR and SR, in the machining of SKH 57 high-speed steel. Statistical analysis of experimental data were obtained using the Taguchi experimental design method. As the pulse duration extended, the MRR initially increased to a peak at around 100μs, and then fell. EWR declined as the pulse duration increased at a particular peak current.
Horacio et al (2011) investigated the electrical discharge machining performance characteristics (material removal rate, electrode wear rate and surface roughness) in the EDM process for AISI 1045 steel with respect to a set of EDM input parameters. The predicted values of the parameters showed a good degree of agreement with those observed experimentally.

Patel et al (2009) optimized the process parameters with EDM for ceramic composites. Experiments were conducted with discharge current, pulse on time and duty cycle and gap voltage as typical process parameters. The discharge current was found to be the most significant factor influencing metal removal rate. An increase in duty cycle increased removal rate while surface roughness decreased.

Mohan et al (2004) evaluated the machinability of aluminum silicon carbide composites in EDM process. It is found that pulse duration has an inverse effect on all response variables such as material removal rate, electrode wear rate and surface roughness.

Yan et al (2005) evaluated the machining performance of EDM with titanium metal and studied the feasibility of modifying the surface by adding urea into the dielectric fluid. Effect of adding of urea into the dielectric on material removal rate and electrode wear rate were studied.

2.2.2 Studies on Process Parameters

Kao et al (2010) presented the influence of various process parameters on material removal rate, electrode wear rate and surface roughness with different work piece materials. Second order multi-variable regression model had been used to develop a correlation among criteria like pulse on time, pulse off time and peak current.
Kansal (2005) optimized the process parameters of powder mixed electrical discharge machining. Response surface methodology has been used to plan and analyze the experiments. Pulse on time, duty cycle, peak current and concentration of the silicon powder added into the dielectric fluid were considered as process parameters to optimize the material removal rate and surface roughness.

Bhattacharya et al (2012) studied the effect of input parameters like current, electrode material, dialectical medium, pulse on time, pulse off time, and powder mixed in dielectric on the material removal rate, tool wear rate, and surface roughness with three different die steel materials. The effect of these parameters on output responses has been analyzed using analysis of variance to establish additive equations for each response and for each material.

Ho et al (2003) reported on the EDM research relating to improve performance measures, optimizing the process variables, monitoring and controlling the sparking process, simplifying the electrode design and manufacture. A range of EDM applications are highlighted together with the development of hybrid machining processes.

Kuang et al (2009) employed RSM to study the material removal rate and electrode wear ratio during the conventional Al powder-mixed EDM of cobalt-bonded tungsten carbide (WC–Co). The experiments have been conducted under finishing conditions with low level of discharge current of 3A.

Tsai et al (2001) investigated a semi-empirical model for surface finish of workpiece in EDM by employing dimensional analysis based on pertinent process parameters such as peak current, pulse duration, electric polarity and properties of materials. In addition, the parameter of the model
has been fitted based on the experimental data generated by the DOE procedures. The results showed that the model was dependent on work and tool materials hence constant parameters could be used for various work and tool materials.

Marafona et al (2009) showed in his presentation that the material removal rate was dependent on the work piece hardness and its interactions with other input parameters. The material removal rate was predicted with an average error of 1.06%. It was also demonstrated that work piece surface roughness was dependent on the work piece hardness and other input parameters. The additive model predicted the work piece surface roughness values with an average error of 0.4%.

Narender Singh et al (2004) investigated the effect of pulse current, pulse on time and flushing pressure on the responses of material removal rate, tool wear rate, taper, radial overcut and surface roughness on electric discharge machining of cast AI-MMC with 10% SiCp reinforcement. Tool wear rate was also found to be higher and larger than the material removal rate for higher pulse current and pulse on time. Due to this fact, the dimensional accuracy was affected. The flushing pressure of the dielectric had considerable effect on the material removal rate and tool wear rate.

Gostimirovic (2011) experimentally investigated that there was an optimal discharge energy which yielded maximum material removal rate. The material removal rate increased with the increase of discharge current for optimal discharge duration. The discharge energy caused uniform increase of gap distance. When the discharge energy was increased, the gap distance exerted greater influence on accuracy of EDM. Surface roughness directly depended on the discharge energy. Moreover, the discharge current was more significant than the discharge duration.
Han et al (2008) proposed a method in which the potential difference was measured at the end of the discharge to avoid the influence of the discharge noise. The experimental results showed that a better sensitivity and resolution could be obtained using the voltage peak value which appeared at the end of discharge, when compared with the method, which used the difference that appeared at the beginning of discharge.

Byung et al (2010) studied the tool wear problem which was based on the mobility’s of electrons and ions in the plasma channel. The material removal volumes of both the electrode and the work piece were compared as functions of the gap voltage. The material removal difference according to the capacitance was also investigated. The tool wear ratio was calculated under different EDM conditions for reducing the tool wear ratio.

Ponappa et al (2010) investigated the effect of process parameters such as pulse on time, pulse-off time, voltage gap and servo speed on surface finish and reduced taper during EDM of magnesium nano alumina composites. They found that the pulse-on-time and the servo speed were the most influencing factors on surface finish and reduced taper.

Yusuf Keskin et al (2006) investigated the effects of machining parameters on surface roughness in EDM. Surface roughness showed an increasing trend with increase in the discharge duration. The interaction between spark time and power to surface roughness was found to be statistically significant.

Lin (2002) experimentally investigated the effects of attached magnetic force to electrical discharge machining. Optimal machining parameters were determined based on Taguchi method. The MRR of magnetic force assisted EDM was almost three times as large as the value of standard EDM. The lower relative electrode wear ratio was improved from
1.03% to 0.33% with the magnetic force assisted EDM. Surface roughness of the magnetic force assisted EDM was less than that of standard EDM. The average value of surface roughness reduced from 3.15 to 3.04µm.

2.2.3 Studies on Different Methodology

Many researchers adopted the response surface methodology to various manufacturing processes such as electro chemical machining and electric discharge machining characteristics in order to optimize machining parameters.

Marimuthu (2005) investigated that efficient utilization of design of experimental techniques which integrated a scientific approach in establishing a welding process.

Marimuthu (2003) developed mathematical equations using five factors and five level factorial technique to predict the geometry of the weld in the deposition of satellite 6 (Co-Cr-A) alloys onto carbon steel valve seat rings (ASTM A105).

Scott et al (2005) used a factorial design requiring a number of experiments to determine the most favourable combination of the wire electrical discharge machine variable parameters. They found that the discharge current, pulse duration and pulse frequency were the significant control factors affecting the material removal rate and surface finish, while the wire speed, wire tension and dielectric flow rate had the least effect.

Myers et al (2002) proposed the response surface methodology using design of experiments which was a collection of mathematical and statistical technique useful for developing, improving and optimizing the process.
Simul et al (2008) used a face centered central composite design approach to develop a mathematical model for material removal rate and surface roughness. Eighteen experiments were conducted based on the design matrix and the model was found to be adequate. According to the model developed, the surface roughness increased with the increase of pulse on time.

Chiang (2007) explained the influences of pulse current, pulse on time and voltage on the responses of material removal rate, electrode wear ratio and surface roughness. The experiments were planned according to a central composite rotatable design matrix and the influences of parameters and their interactions were investigated using ANOVA. A mathematical model was developed and claimed to fit and predict material removal rate accurately with a 95% confidence. Modelling and analysis of the rapidly re-solidified layer of spheroid graphite cast iron on the EDM process used the response surface methodology. The conclusions revealed that the quantity and area fraction of graphite particle were the most influential factors on the layer thickness and ridge density.

Tsai et al (2001) established several surface models based on neural networks and the effects of electrode polarity were taken into account. Subsequently, a semi-empirical model was developed which was dependent on the thermal, physical and electrical properties of the work piece and electrode together with pertinent process parameters.

Paulo Davim et al (2008) predicted the surface roughness of Al composite using Artificial Neural Network. Experiments were conducted using an L27 orthogonal array with three levels for each factor. The network was trained using Error Back-Propagation Training Algorithm (EBPTA). It was reported that the performance of ANN prediction model, though adequate, could be improved by defining more number of levels for input process parameters.

Tsai et al (2004) determined the deficiency of machining accuracy due to the deposit of molten metal on the work piece surface in the EDM process.

Wu (2005) discussed the improvement of the machined surface of electrical discharge machine by adding aluminum powder and surfactant into dielectric fluid.

Assarzadeh (2012) optimized the process parameters involved in Powder-Mixed Electrical Discharge Machining (PMEDM). Aluminum oxide ($\text{Al}_2\text{O}_3$) fine abrasive powders with particle concentration and size of 2.5–2.8g/L and 45–50μm respectively were added into the kerosene dielectric liquid of a die-sinking electrical discharge machine. It was shown that the error between experimental and anticipated values at the optimal combination settings of input variables were all less than 11%, confirming the feasibility and effectiveness of the adopted approach.

2.2.4 Studies on Scanning Electron Microscope Analysis

Kruth and Stevens (1995) completed a metallographic examination of the white layer, which was the upper recast layer of the heat-affected zone, in die skinning EDM. The obtained results indicated that the micro cracks were found to be perpendicular to the machined surface and the dendrites were oriented in the direction of the maximum cooling gradient and were perpendicular to the machined surface.

Chen et al (1999) investigated and compared the effect of kerosene and distilled water dielectrics. During machining with water as dielectric, it
got oxidized on the work piece surface and the surface layer provided higher material removal rate.

Caydas et al (2008) developed a model to predict electrode wear and white layer thickness in die-sinking EDM process by central composite rotatable design method with the three input process parameters.

Chiang et al (2008) studied the silicon particle effect of Al-Si alloys on the rapidly resolidified layer. The effects of silicon particles included their content, area fraction and intercept length of primary silicon particles. The layer thickness, surface roughness and ridge density on the rapidly resolidified layer were considered in the performance evaluation.

Ekmekci (2009) investigated the characteristics of EDM surfaces of normalized, quenched, and tempered-treated steels in kerosene and deionized-water dielectric liquids. The recast layer during electrical discharge machining process caused the formation of micro cracks in the very hard and brittle material. The results revealed that base material properties and white layer composition had a distinctive function on crack formation that resulted in different crack network layouts on the surface and penetration depths in the substrate. Surface cracks which initiated at the surface, travel down perpendicularly toward the interferential zone and terminated at this interference due to an increase in non-homogeneties of metallurgical phases within the white layer.

Rebelo et al (1998) analyzed the surface integrity of steel in the EDM process by increasing the pulse energy in machining to determine the increase in arbitrary overlapping of surface craters, density and penetration depth of the cracks in the rapidly re-solidified layer.
Ramaswamy et al (2005) conducted experiments to study the cooling and solidification at the top surface of the work piece. Pockmarks, globules, cracks and micro cracks were analysed whose thickness and density depended on the process conditions.

Lee et al (1988) developed empirical relationships between the EDM process parameters of current and pulse on time and thickness of the white layer.

Lee et al (2003) conducted experiments on EDM of tungsten carbide work piece surface.

It was observed that there was no significant difference between the hardness of the electrical discharge machined surface and the original hardness of the tungsten carbide work piece surface. It was also observed that with increase of peak current and pulse duration, number of micro-cracks increased. The micro-cracks seem to disappear when the peak current and pulse duration were set at very low levels.

Gostimirovic et al (2012) conducted experimental investigation to find the influence of process parameters on material removal rate and surface integrity in EDM. EDM experiments had been conducted to investigate the machined work piece surface integrity, including the microstructures, surface topography, micro-cracks, composition and hardness under a wide range of machining conditions.

Khanra et al (2007) predicted that electrode wear was reduced due to the restriction of the temperature raise of the wire material in the WEDM process.
Pham et al (2004) pointed out that errors from different sources such as the accuracy and repeatability of positioning of the machine, electrode dressing, jigs and fixtures and electrode wear directly affected the accuracy of the Micro-electrical discharge machine process.

Aligiri et al (2010) proposed a new tool wear method to solve the problem of geometrical inaccuracy of machined hole depth in Micro-electrical discharge machine. The research work mainly focused on the influence of tool steel on the surface quality of machined surface.

Guu et al (2005) investigated about the effect that very high temperature, produced at the point of the spark, on the work material surface, due to electrical discharge energy. The depth of the micro-cracks on the EDM ranges from 1272 to 1873µm increasing significantly with the pulsed current and pulse on duration. The maximum depth of the micro cracks could be determined from the distance between the highest peak and the lowest valley. The surface roughness on the machined surface varied from 103 to 172 µm. From these results, it was clear that a higher pulse current and longer pulse on duration caused a poorer surface finish. This attributed to the fact that a higher pulse current and longer pulse on duration might cause more frequent cracking of the dielectric fluid and there was also more frequent melt expulsion leading to the formation of deeper and larger craters on the work piece surface.

Shabgard et al (2011) predicted white layer thickness and depth of heat-affected zone and in that work plasma flushing efficiency was analyzed. The conclusions revealed that the quantity and area fraction of graphite particle were the most influential factors on the layer thickness and ridge density.
Wong et al (2003) reported that the volume and size of microcraters using single RC-pulse discharges were more consistent for lower energy than for higher energy discharges.

In recent years, Neural Networks have become a very powerful tool in modelling inter-relationships between input and output parameters of many complicated systems. Various studies on the prediction of mechanical properties of composites using ANN have been carried out.

Panda et al (2005) prefigured the surface roughness and cutting geometry of EDM with tungsten carbide. They used Multivariable regression model and back propagate on neural network model.

Tarng et al (1995) used a neural network system to determine settings of pulse duration, pulse interval, peak current, open circuit voltage, servo reference voltage, electric capacitance and table speed for the estimation of cutting speed and surface finish.

Abdullah (2009) developed a neural network model to predict the cutting tool stresses. A back propagation algorithm was developed for training the network. The best fitting set was obtained with ten neurons in the hidden layer in the model.

Cao Fenggou (2004) optimized the processing parameters in the EDM sinking process with the application of Artificial Neural Networks (ANN), which utilized the mirror processing conditions. It was proved that the automatic determination and optimization by artificial neural networks of EDM sinking processing parameters were efficient.
2.3 STUDIES ON WEDM

WEDM is an essential operation in several manufacturing processes in some of the industries, where precision and accuracy are important. Several researchers have attempted to improve the performance characteristics namely the surface roughness, cutting speed, dimensional accuracy and material removal rate.

However, the full potential utilization of this process is not completely solved because of its complex and stochastic nature and more number of variables involved in this operation.

2.3.1 Studies on Work Piece Material

Kanlayasiri et al (2007) conducted a study on the effect of machining variables of the WEDM process on newly developed DC 53 die steel by using Design of experiments and regression model. The pulse on time and peak current were the important machining parameters for the increase in surface roughness.

Hewidy et al (2005) established the adequacy of response surface methodology approach to machine Inconel 601 material under acceptable volumetric material removal rate, wear ratio and surface roughness. With the increase of peak current, volumetric material removal rate and surface roughness were found to be increasing. When the duty factor decreased and increased, the wire tension reached 8mm$^3$/min and the surface finish was less than 1µm.

Ozgedik et al (2006) investigated the machinability of standard GGG40 nodular cast iron by WEDM using different electrical input parameters (machining voltage, current, and wire speed) and their effect on
the high machining efficiency for nodular cast iron. The discharge energy increased with the increase of the voltage and the current resulting in the removal of the metal. When the open circuit voltage increased up to 80, 100, and 270 V, the machining stability was improved and the cutting rate substantially increased. It was seen that increasing the open circuit voltage, discharge current, and wire speed caused the increasing of cutting rate and surface roughness.

Cabanes et al (2008) investigated on-line supervision system to monitor and prevent the breaking of wire in WEDM by readjusting the machining parameters. The process performance, through a novel wire breakage monitoring and diagnosing system, consisted of two well-differentiated parts viz., the Virtual Instrumentation System (VIS) that measured relevant magnitudes, and the Diagnostic System (DS) that detected low quality cutting regimes and predicted wire breakage. It has been successfully validated through a considerable number of experimental tests performed on an industrial WEDM machine for different work piece thicknesses.

Ahmet et al (2004) investigated the effect of machining parameters namely open circuit voltage, pulse duration, wire speed and dielectric fluid pressure on surface integrity of AISI D5 tool steel used in manufacturing die and mould components by wire electrical discharge machining process. It was found that the intensity of the process energy affected the amount of recast and surface roughness as well as micro cracking, the wire speed and dielectric fluid pressure not seeming to have much of an influence.

Schoth et al (2005) presented future trends and developments in WEDM with smaller wires (<20μm) with new wire guiding and sensing for different materials, especially ceramics with micro parts in a variety of conductive materials with aspect ratios upto 100.
Kozak et al (2004) presented a work about the broad capabilities to encompass the production, aerospace and automotive industries and virtually all areas of conductive material machining.

WEDM provides the best alternative or sometimes the only alternative for machining conductive, exotic, high strength and temperature resistive materials, conductive engineering ceramics with the scope of generating intricate shapes and profiles.

Murphy and Lin (2000) developed a combined structural-thermal model using energy balance approach to describe the vibration and stability characteristics of an EDM wire. High-temperature effects were also included resulting from the energy discharges. The thermal field was used to determine the induced thermal stresses in the wire. An equilibrium and Eigen value analysis (for small vibrations about the computed equilibrium) showed that the transport speed influenced the stability of the straight equilibrium configuration. The wire had an extended residency time in the kerf and the wire thermally buckled.

Puri and Bhattacharyya (2003) performed an analysis on wire tool vibration in order to achieve a high precision and accuracy in WEDM with the system equation based on the force acting on the wire in a multiple discharge process. It was clarified from the solution that the wire vibration during machining was mainly manipulated by the first order mode \((n = 1)\). In addition, a high tension without wire rupture proved always beneficial to reduce the amplitude of wire-tool vibration.

Laio et al (2004) analyzed the effect of each relevant factor on surface roughness. Appropriate values of all parameters were chosen and a fine surface of roughness \(Ra = 0.22\mu m\) was achieved. The improvement was limited because finishing process became more difficult due to the occurrence
of short circuit attributed to wire deflection and vibration when the energy was gradually lowered.

Spedding (1997) developed a model to evaluate surface roughness, cutting speed, dimensional accuracy and material removal rate for the WEDM process.

Hwa (1999) identified the process parameters (Open gap voltage and pulse-on time) as significant influencing parameters on material removal rate in wire-cut EDM of aluminum composites.

Yang et al (2012a) analyzed the variations in material removal rate, surface roughness and corner deviation for WEDM process with pure tungsten as work material. A fusion technique that comprised response surface methodology and back-propagation neural network integrated, simulated annealing algorithm was used. Higher pulse on time caused the high material removal rate but at the same time it produced rough surface.

Ramakrishnan et al (2006) used Taguchi’s robust design approach for wire electrical discharge machine. It was found out that increase in pulse on time further than level three, enhanced the surface roughness and wire wear ratio in consequence of greater discharge energy and increase in wire tension caused wire breakage.

Jun Qu (2002) investigated the surface integrity and roundness of cylindrical wire EDM with carbide and brass. Two sets of experiments were conducted to identify the effects of the part rotational speed, wire feed rate and pulse on time on the surface finish and roundness. First set of experiment was conducted to verify the surface finish model. Second set of experiment demonstrated that good surface finish and roundness could be achieved in the
cylindrical wire EDM process. The macro-ridges, surface craters, recast layers and heat-affected zones were observed and their sizes were estimated.

Yanda et al (2010) studied the influence of various process parameters on material removal rate, electrode wear rate and surface roughness with different workpiece materials.

Huang et al (2003) presented the use of grey relational and signal to noise ratio analysis which also displayed similar outcome representing the influence of feed and pulse on time on the material removal rate.

Grum and Kisin (2003) established the relationship between the microstructure and surface roughness of the machined surface from the perspective of the size of the soft phase in the microstructure of aluminum-silicon alloys. The morphology of Al-Si alloys was affected by both the chemical composition and the condition of solidification.

Yan et al (2005) performed experiments on a FANUC W1 CNC wire electrical discharge machine for cutting both the 10 % and 20 % by volume of Al₂O₃ particles reinforced 6061Al alloys-based composite and 6061Al matrix material itself. Results indicated that the cutting speed (material removal rate), the surface roughness and the width of the slit of cutting test material significantly depended on volume fraction of reinforcement (Al₂O₃ particles).

Hsue et al (1999) introduced a useful concept of discharge-angle Cθ and presented a systematic analysis for metal removal rate in corner cutting. Discharge-angle Cθ and metal removal rate dropped drastically to a minimum and then recovered to the same level of straight-path cutting sluggishly. The amount of the drop at the corner apex was dependent on the angle of the turning corner. The drastic variation of sparking frequency in corner cutting
could be interpreted as the symptom of the abrupt change of MRR. The sudden increase of gap-voltage could also be interpreted as the result of abrupt MRR drop.

Lok et al (1997) analysed the mechanism of metal removal in wire electrical discharge machining mainly involves the removal of material due to melting and vaporization caused by the electric spark discharge generated by a pulsating direct current power supply between the electrodes.

Tosun et al (2004) investigated the effect and optimization of machining parameters on the kerf (cutting width) and material removal rate in the WEDM process.

The results showed that open circuit voltage was three times more important than the pulse duration for controlling the kerf, whereas open circuit voltage for controlling the MRR was about six times more important than pulse duration.

Aminollah et al (2008) developed a new approach to improve the surface roughness and roundness in the turning wire electrical discharge machine by statistical analysis. It was concluded that only power had a significant outcome on the surface roughness and no other factors had a significant outcome on roundness.

Puri et al (2003) investigated the wire lag phenomenon in wire cut electrical discharge machining process and found that the trend of variation of the geometrical inaccuracy was caused due to wire lag with various control parameters. They found that the optimal parametric settings with respect to productivity, surface roughness and geometrical inaccuracy due to wire lag were different.
Kuriakose et al (2005) used titanium alloy (Ti-6Al-4V) as the work material and conducted experiments based on Taguchi L18 orthogonal array. Non-dominated sorting genetic algorithm was employed to determine the optimal process parameters that would optimize the cutting velocity and surface roughness of the WEDM process.

Sankar et al (2005) modelled the WEDM process to predict the responses, cutting speed, surface finish and dimensional deviation as the function of different control parameters and determined the main influencing factors for each given machining criterion.

Kuang et al (2008) developed multi-objective optimization methods to optimize the WEDM process, considering mean pulse current, pulse on time and pulse off time as the input parameters and material removal rate and surface roughness as the process responses.

Mahapatra (2007) identified discharge current, pulse duration, pulse frequency, wire tension, delay time and dielectric fluid as the major machining parameters affecting material removal rate, surface finish and cutting width of the WEDM process.

Puri et al (2005) reported that the white layer depth increases with increasing pulse on time during the initial cut. It also decreased with increasing pulse on time during trim cutting. Break even trim cutting speed is detected to be 3 mm/min.

Hargrove et al (2006) investigated the effect of WEDM process parameters such as discharge voltage and pulse on time on the damaged layer thickness of a machined work piece using low carbon steel (AISI 4340) as the cutting material. The optimum parameters for this machining process was selected such that the condition of machine cutting speed was 1.2 mm/min, on
time pulse was 8μs and no load voltage was 4volt. The analyzed results had a good agreement with testing results.

Huang et al (1999) investigated experimentally the effect of various machining parameters on the gap width, surface roughness and the depth of white layer on the machined work piece (SKD11alloy steel) surface. They adopted the feasible-direction non-linear programming method for determination of the optimal process settings.

Nihat et al (2003) studied the effect of the cutting parameters on size of erosion craters (diameter and depth) on wire electrode in WEDM. It was found that increases in the pulse duration, open circuit voltage and wire speed increased the crater size, whereas increase in the dielectric flushing pressure decreased the crater size.

Ozdemir et al (2005) investigated the ability of standard GGG40 nodular cast iron by A300 Fine Sodick Mark XI WEDM using different parameters. The increase in surface roughness and cutting rate clearly followed the trend indicated with increasing discharge energy because of an increase in current and pulse on time because the increased discharge energy produced larger and deeper discharge craters. Three zones were identified in rough regimes of machining for all samples viz., decarburized layer, heat affected layer, and bulk metal.

Montgomery et al (2000) explained to use Design of Experiments to execute the accurate and more efficient analysis. The analysis of their results was of vast importance in experimental work.

Chiang (2006) observed that grey relational analysis found wide application areas for the optimization of the wire electrical discharge machining process of Al₂O₃ particle reinforced material (6061 alloy) with
multiple-performance characteristics. The machining parameters like the cutting radius of working piece, pulse on time and pulse off time of discharging, the arc on time and the arc off time of discharging, the servo voltage, the wire feed and water flow were considered for optimization with considerations of multiple performance characteristics, such as the surface removal rate and the maximum surface roughness. It was clearly shown that the above performance characteristics in the WEDM process were greatly improved.

Aggarwal et al (2008) optimized by finding a good set of conditions that would meet all the goals. It was not necessary that the value of desirability was always 1.0 as the value was completely dependent on how closely the lower and upper limits were set relative to the actual optimum.

Yan et al (2007) presented a feed forward neural network using a back propagation-learning algorithm for the estimation of the work piece height in WEDM. The developed hierarchical adaptive control system enabled the machining stability and the machining speed improved by 15% when compared with a commonly used gap voltage control.

Spedding et al (1997) considered pulse width, pulse on time, pulse off time, wire mechanical tension and injection set point as the input process parameters and surface roughness and surface waviness were the responses and then modelled the WEDM process using response surface methodology and artificial neural network.

Ramakrishnan et al (2006) developed ANN-based models and multi-response optimization technique to predict and select the best cutting parameters of the WEDM process, while considering pulse on time, delay time, wire feed speed and ignition current as the process parameters and MRR and surface finish as the performance characteristics.
Sarkar et al (2010) applied a feed forward back propagation neural network to develop an appropriate machining strategy for maximum WEDM process criteria yield, while considering pulse on time, pulse off time, peak current, wire tension, dielectric flow rate and servo reference voltage as the control parameters and cutting speed, surface roughness and wire offset as the process responses.

Applying response surface methodology technique, Chen et al (2010) integrated back propagation neural network and simulated annealing algorithm to determine the optimal parameters setting of a WEDM process.

The literature review summarized that a good volume of research have been carried out on the mechanical and chemical properties and machining characteristics of various steel materials. T90Mn2W50Cr45 was one type of cold rolled steel material which was used in making of dies. But T90Mn2W50Cr45 steel material was not considered for the EDM or WEDM processes. Only limited amount literature is available encompassing various aspects such as microstructure, mechanical properties and responses as well as modelling with a Design of experiment and ANN model. Based on the literature review in the present investigation, an attempt has been made to study the electrode wear, rapidly resolidified layer thickness, material removal rate and surface roughness, microstructure and machining characteristics of T90Mn2W50Cr45 steel material. Mathematical Models are developed for various responses like Material Removal Rate, Electrode wear rate, Surface Roughness and re solidified layer thickness for EDM process. Similarly, T90Mn2W50Cr45 steel material is also used in WEDM process to conduct the experiments and mathematical model for various responses like Material Removal Rate, Wire Wear rate, surface finish and resolidified layer thickness are developed using RSM and statistical software carried out. Effect of using T90Mn2W50Cr45 steel material for the EDM and the WEDM processes are compared in the conclusion Chapter 8.