CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Electrical Discharge Machining (EDM) is a non-traditional machining process that has become a well-established machining option in manufacturing industries throughout the world. It has replaced drilling, milling, grinding and other traditional machining operations in different aspects. Micro-EDM, a recent development, is found to be a cost-effective process for fabrication of micro-tools, micro-components and micro-features with good dimensional accuracy and repeatability. This chapter provides a review of the published literature on EDM and micro-EDM to place the research problem in perspective.

2.2 DIFFERENT ISSUES IN MICRO-EDM

There are many parameters that influence the machining performance of micro-EDM, some of which are given in Figure 2.1.

Several studies focussed on the influence of the most relevant micro-EDM factors to achieve high MRR, low TWR and good surface finish.
Figure 2.1 Fish-bone diagram of various influencing parameters

Although several researches have been carried out on different tool steel and electrode, extensive research on the micro-EDM of EN24 die steel using different electrodes is still scarce. Therefore, it exhibits a great need to analyze the performance and influences of different electrodes and the outcome of the different parameters such as MRR, TWR, surface roughness (SR), heat affected zone (HAZ), circularity error, overcut, etc. So in this present work, a study was carried out to obtain quality micro-holes with high MRR and better dimensional accuracy using different electrodes such as W, Cu, CuW and AgW.

2.2.1 Influences of Discharge Energy

The factors influencing the machining performance largely depend on the discharge energy applied for machining. The various issues such as surface roughness, heat affected zone, micro-hardness and crack formations
and machining quality of the workpiece are determined by the amount of energy released in every spark (Masuzawa 2000).

Jahan et al. (2009a) studied the performance of die-sinking micro-EDM of tungsten carbide using different electrodes. They observed that the lower discharge energy shows better surface finish. Lower input energy proves to show reduction in surface roughness and burr width.

Somashekar et al. (2010) investigated the influence of discharge energy and predicted that the increase in discharge energy leads to increase in MRR. Wong et al. (2003) developed a single spark generator to study the erosion characteristics from the micro-crater size. The result shows that the volume and size of the micro-craters are found to be more consistent at lower energy discharges and the specific energy required to remove the material is found to be significantly less at lower energies (< 50μm) when compared with that at higher energies. The estimated erosion efficiency of MRR at low-energy discharges is found to be seven to eight times higher than that at higher-energy discharges. This can be due to occurrence of resolidified or recast layer largely associated with high energy discharges, apart from arcing problems.

Gostimirovic et al. (2012) examined the influence of discharge energy during the micro-EDM process of manganese-vanadium tool steel using copper electrode. The results revealed that MRR and HAZ increase due to increase in discharge energy.

2.2.2 Influences of Dielectric Fluids

The two most commonly used fluids are petroleum-based hydrocarbon mineral oils and deionized water. These dielectrics have the proper effects of concentrating the discharge channel and discharge energy
but they might have a difficulty in flushing the discharge products. Research has been done using different dielectric fluids like kerosene and de-ionized water.

The basic need of dielectric in EDM is to provide a momentary plasma column/channel for electron to flow maintaining sparking only. In order to maintain the desired integrity of workpiece and to enhance the performance of micro-EDM, it is essential to properly choose a dielectric and associated spark discharge. Discharge depends on pyrolysis (plasma) effect in dielectric fluid. Since different dielectrics have different cooling rates and compositions, the choice of dielectric plays an important role in the micro-EDM process. Many research works proved that ceramic powder added to dielectric increases the breakdown characteristics of the dielectric fluid.

Chung et al. (2007) experimented with micro electrical discharge milling using tungsten carbide (WC) as tool electrode and stainless steel plate as workpiece, with deionized water as a dielectric fluid. They used deionised water with high resistivity to minimise the machining gap and investigated machining characteristics such as tool wear, machining gap and machining rate. The result shows that when the resistivity of deionised water increased, to minimise the gap resistance the machined gap should be decreased. Kibria et al. (2010), investigated the performance criteria like MRR, TWR, overcut, diameter – variation at entry and exit of the drilled hole and surface integrity during machining of titanium alloy (Ti-6Al-4V) using different types of dielectric such as kerosene and deionised water, boron carbide (B$_4$C) powder was suspended in kerosene and deionised water. The experimental results revealed that MRR and TWR are higher using deionised water than kerosene. It is surprising to observe that despite higher order TWR; MRR could be higher. This could be due to setting of smaller inter-electrode gap inducing occasional (transient) arcing. When particles like boron carbide suspended
dielectrics are used, MRR is found to increase. Scanning electron microscopy (SEM) indicates that the thickness of white layer is less on machined surface when deionised water is used as compared to kerosene. Presence of particles like B$_4$C can reduce the dielectric constant of the dielectric material facilitating high order spark intensity and higher MRR.

Song et al. (2009) attempted to produce an electrolytic, corrosion-free hole in micro-electrical discharge drilling (EDD) of WC-Co with deionised water. The WC-Co is susceptible to electrolytic corrosion when deionised water is used as the working fluid with a DC power source for the RC circuit. To suppress this electrolytic corrosion, a bipolar pulse power source reduces the positive polarity period of the workpiece by periodically alternating the polarity of the workpiece and electrode and decreases the average gap voltage at the machining gap. Since the electrolytic corrosion is an electrochemical reaction between the side of the electrode and the surface of the workpiece, the usage of the triangular electrode with small side area reduces these reactions. The bipolar pulse power source is more effective in reducing electrolytic corrosion with low electrode wear and high machining speed than the DC power source for an RC discharge circuit. Normally hard, brittle materials like WC are spark eroded with reverse polarity and also dielectric such as kerosene or paraffin is used to avoid such problem.

Prihandana et al. (2009) studied the effect of micro-powder suspension and ultrasonic vibration in micro-EDM processes using the Taguchi method. They found that copper as a workpiece material with the addition of micro - MoS$_2$ powder to dielectric and superimposed ultrasonic vibration increases the MRR. From this study, it is possible to infer the contributing influence while MoS$_2$ can serve to reduce the dielectric effect, the superimposed oscillation can facilitate clean inter electrode gap by
effective removal of the debris, and also oscillation can induce sequencing reduced with electrode gap favouring higher order spark intensity.

Yeo et al. (2007) investigated the effects of using silicon carbide (SiC) nano powder suspended in dielectric like Idemitsu synthetic electric spark oil, Daphne cut HL-25 on crater characteristics for micro-EDM. The results show that the craters with smaller diameters and more consistent circular shapes and depths are produced for dielectric with additive than without additive. The presence of nano powder can control the plasma channel (resistance) and thereby avoid any surge effects. Kagaya et al. (1990) experimented with the deep micro-hole drilling using water as a working fluid for the fabrication of narrow slit. The optimum condition for narrow slit fabrication was investigated concerning the electric discharge circuit and combinations of electrode, workpiece materials and electrode polarity. The result shows that it is possible to fabricate fine slits as narrow as 20μm wide and 3mm long with fairly fine surface roughness of around 1μm. Chow et al. (2007) investigated micro-slit EDM process along with small discharge energy and SiC powder in pure water (distilled water). The results indicated that the addition of SiC powder would increase working fluid electrical conductivity, extrude the debris easily and increase the MRR.

It is seen that SiC suspended deionised water facilitates higher order depth of removal and machining is mostly insensitive to pulse duration. However, plain deionised water exhibits lower order machining depth sensitivity to pulse duration. The use of deionised water as dielectric is preferred to kerosene, owing to increased MRR. However, deionised water can cause problems such as hydrogen embrittlement, corrosion and occasional explosion. This requires a lot of caution in using deionised water. Addition of particles such as B₄C, SiC can enhance the machining performance. EDM
with dielectric containing suspended particles has been used to enhance the hardness of work materials.

In sinking EDM, however, hydrocarbon dielectrics are normally used because surface roughness is better and tool electrode wear is lower compared to de-ionized water (Kunieda et al. 2005). Also with deionised water there is a possibility of hydrogen embrittlement/cracking.

Kaminski and Capuano (2003) investigated the machining of micro-hole and stated that the dielectric fluid used is composed basically from hydro-carbons that are cheaper than synthetic dielectric fluids. To sum up from the literature highlighted the hydro-carbon oil is also one of the most suitable dielectric for the micro-EDM process.

2.2.3 Influence of Pulse Characteristics

As micro-EDM is a thermo-electric process, the pulsed discharge is responsible for removing metal through melting and evaporation.

Han et al. (2004) developed a new transistor type isopulse generator and servo feed control to improve the machining characteristics of micro-EDM. They observed that the pulse duration can be reduced to around 30ns which is ideal for finishing and obtained a removal rate of about 24 times higher than that of the conventional RC pulse generator with a constant feed rate (in both semi-finishing and finishing conditions). The advantages of using servo feed control in finishing are considerably greater than in semi finishing, whereas the transistor type isopulse generator proved more useful in semi-finishing than in finishing.

However, it is difficult to infer the contribution of an individual parameter (pulse duration and servo feed) to machining performance.
Reducing the pulse duration can minimise the spark intensity and consequently favour better surface finish. However, minimising the pulse on duration, with consequent increasing pulse off duration can impair the machining. Thus, one can anticipate a mixed mode of conflicting influence.

Kim et al. (2010) introduced a novel hybrid micromachining system using a nanosecond pulsed laser and micro-EDM. The feasibility and characteristics of the hybrid machining process were compared to conventional EDM and laser ablation. It was experimentally proved that the machining time can be effectively reduced in both EDM drilling and milling by rapid laser pre-machining prior to micro-EDM. Laser ablation can enhance the hardness of the surface (effect of laser glazing), and consequently facilitate improved micro-EDM. Son et al. (2007) investigated the influences of EDM pulse condition on the micro-EDM properties. Voltage, current, and on/off time of the pulse were selected as experimental parameters based on their relationship to the MRR. The pulse condition is significant, in that it particularly focuses on tool wear, MRR, and machining accuracy. The experimental results showed that the duration of pulse off/on ($t_{\text{off}}/t_{\text{on}}$) time considerably affects machining properties and comparatively shorter pulse on duration is preferable to make accurate machining with a higher removal rate and lower TWR. More than pulse on, pulse off duration is a key factor in sustaining the process. The wear of tool electrode was measured and the results are shown in Figure 2.2. Koyano and Kunieda (2010) proposed an electrostatic induction feeding method to achieve high accuracy and removal rate in micro-EDM. In the new method, only a single discharge occurs for each cycle of the periodic pulse voltage. The results showed that the machining speed is four times higher and the heat damage on the machining surface is less compared to the conventional machining with pulse generator.
Yeo et al. (2009a) developed a new pulse discriminating technique for monitoring micro-EDM. The developed system employed current pulse as the main detecting parameter and it was tested on micro-EDM drilling and micro-EDM milling; pulse distributions were analysed. The experimental results showed that the system is able to reduce the machining time by more than 50% and the accuracy of the resulting features is increased.

Jahan et al. (2009b) investigated the influence of major operating parameters on the performance of micro-EDM of WC with a focus on obtaining quality micro-holes with both transistor and RC-type generators. The experimental results showed that RC-type generator can produce micro-holes with good surface quality with rim free of burr-like recast layer, good circularity and dimensional accuracy. Figure 2.3 shows the comparative values of spark gap for transistor and RC circuit, respectively, at different setting of machining conditions for the micro holes. As the discharge energy can be reduced easily in RC type using very low capacitance, it is more suitable for fabricating micro-structures and RC type pulse generator can produce smoother surface compared to that of transistor type in the micro-EDM of WC. This also supplements the need for reverse polarity for spark erosion of WC.
Figure 2.3 Comparison of spark gap of micro-holes for transistor-type and RC-generator (a) Spark gap of micro-holes in transistor-type (b) Spark gap of micro-holes in RC-type

It is seen that with transistor type generator a wide variation in spark gap, gap voltage and resistance occurs. However, in RC circuit, only limited order of variation can be seen.

Liu et al. (2010) investigated the influence of pulse generator to produce small input energy pulses with high precision systems. An indepth analysis was also made on the correlation between the discharge pulses and the machining parameters in order to have an overview of process capability. The results revealed that high accuracy machining in the range of less than 1µm can be achieved.

Long et al. (2012) studied the new micro-EDM deposition process using transistor type and RC-type generators. From the results, it is observed that both pulse generators can be applied in the micro-EDM deposition process. However in the transistor type, the short circuit damages the deposited material even though it is easy to obtain the same single discharge energy. But the RC type generator is extensively used in micro-EDM
deposition process with the high deposition rate as it adjusts discharge energy according to the discharge gap state.

2.2.4 Influence of Various Electrodes

Jahan et al. (2009a) experimented with ultra die-sinking micro-EDM of WC using different electrodes and found that CuW electrode achieves the highest MRR followed by AgW. Muttamara et al. (2010) studied the micro-EDM performance on silicon nitride using different electrode materials and observed that Cu electrode gives the highest MRR, followed by the CuW and AgW electrodes. Sanchez et al. (2001) investigated the machining of B₄C and SiSiC, using different electrode materials and observed that Cu and Cu-Gr electrodes achieve maximum MRR and graphite as electrode material shows the highest electrode wear rate. Ramaswami and Louis Raj (1973) studied erosion of high speed tool steel HSS with three different electrodes such as copper, brass and aluminium and it is proved that copper shows better MRR, wear ratio and surface finish than other electrodes. The machining performance of AISI H13 die steel using differently shaped copper electrode was carried out by Pellicer et al. (2009).

Singh et al. (2004) investigated the electrical discharge machining of hardened EN-31 tool steel using copper, copper tungsten, brass and aluminium electrodes and concluded that copper is comparatively a better electrode as it shows good surface finish, high MRR, low diametral overcut and less electrode wear. The good surface finish with high MRR and low tool wear is attributed to possible side erosion of the machined holes. The results also revealed that the output parameters of EDM increase with the increase in pulsed current and the best machining rates are achieved with copper and aluminium electrodes. Yeo et al. (2009b) studied the micro-EDM performance using tungsten rod electrode, copper and brass electrodes and it was observed that tube electrodes experience lower tool wear than rod
electrodes. This is due to the enhancement of heat transport through a larger tool electrode area that was exposed to the dielectric. Also tubular electrodes facilitate central flushing tendency.

Soni and Chakraverti (1995) studied the effect of material properties of different electrodes such as copper, brass, copper tungsten, graphite and titanium in electrical discharge machining of HCHCr die steel. It is observed that surface roughness and dimensional accuracy increase with increase of thermal conductivity. It was also found that copper–tungsten is the best electrode material for finish machining whereas for rough machining, graphite is better. Size of crater increases with increase of current which ultimately affects the surface finish.

Nguyen et al. (2012) performed micro-EDM on tempered carbon steel using tungsten electrode. The results revealed that MRR is higher while using deionized water than hydrocarbon oil. It was also observed that MRR reduces with high frequency and short duration of pulse. Possible carbon pick up by the tool electrode (in the case of hydro carbon dielectric) contributes to the observation.

Lee and Li (2003) investigated the effect of machining parameters upon machining characteristics in EDM of WC using Cu, CuW and graphite electrodes and found that the CuW electrode performs better compared to other two electrodes for the EDM of WC.

2.3 PERFORMANCE MEASURES IN MICRO-EDM

The observation of various machine setting parameters such as MRR, TWR, SR, circularity error, overcut, micro-cracks and HAZ in micro-EDM process is reviewed in this section.
2.3.1 Material Removal Rate

MRR is defined as the volume (mm$^3$) of the material removed, divided by the machining time (min). Sundaram et al. (2007) investigated ultrasonic assisted micro-electro discharge machining. They found that introducing ultrasonic vibration of workpiece is significant for higher MRR.

Jahan et al. (2010), investigated the feasibility of machining deep micro-hole in two difficult-to-cut materials, cemented carbide (WC-Co) and austenitic stainless steel (SUS 304), using micro-EDM drilling. The results showed that WC-Co exhibits better MRR than SUS 304. They observed that higher hardness and melting point of WC-Co is a good condition for EDM, in preference to SUS 304.

Put et al. (2001) investigated MRR by altering electrode polarity on a zirconia-based composite and concluded that negative polarity gives the most stable machining conditions with a noticeably lower risk of arcing. Carbide and nitride give higher MRR with positive polarity, whereas boride gives faster machining with negative polarity. However, to minimize the chance of thermal shock and consequence cracking mostly negative polarity is preferred.

Beri et al. (2008) investigated the influences of electrodes made through powder metallurgy in comparison with conventional copper electrode during electric discharge machining. It was found that Cu electrode shows higher material removal rate than Cu-W which is made by powder metallurgy.

Sanchez et al. (2001) studied the performance of various electrodes on ceramic material. It was found that maximum MRR can be achieved using copper (Cu) as electrode and worst results were found with graphite electrode (Gr). Wang et al. (2011) investigated the influence of adhesion composed of
heat-resolved carbon and graphite during the machining of poly crystalline diamond by micro-EDM. The results revealed that an appropriate volume of adhesion on the tool electrode increases MRR and reduces TWR by protecting the electrode.

Lim et al. (2003) investigated the machining performance of high-aspect ratio micro-structures using micro-EDM and it is observed that more material is removed as capacitance value increases.

Gupta et al. (2010) studied the performance analysis of micro-EDM process using pyrolytic carbon. ANOVA was performed to identify the effect of process parameters on the process responses. The results revealed that MRR increases with the increase of gap voltage and a smoother surface is obtained at 110V gap voltage and low capacitance.

Zahiruddin et al. (2012) studied the comparison of energy and removal efficiencies between micro and macro-EDM. The main difference identified is the ratio of energy consumed for material removal with regard to energy distributed into the workpiece and the ratio of total removal volume per pulse with respect to the molten area volume. It was also found that the power density in micro-EDM is approximately 30 times greater and consequently energy efficiency and removal efficiency were significantly greater than macro-EDM.

2.3.2 Tool Wear Ratio

Tool wear ratio (TWR) is defined as the ratio of amount of electrode to the amount of workpiece removed. One of the most difficult output parameters is to calculate TWR in micro-EDM process. Four methods are used to measure the electrode wear ratio by means of measuring weight, length, shape and total volume, respectively. Yu et al. (2004) proposed a
recently developed uniform wear method integrated with CAD/CAM software to generate 3D micro cavities. They found that the uniform wear method compensates the tool wear and helps in regaining the tool shape during machining. The compensation for wear maintains the desired inter electrode gap.

Yoshida and Kunieda (1999) studied the mechanism for minute tool electrode wear in dry EDM. The tool electrode wear is almost negligible for any pulse duration because the attached molten workpiece material protects the tool electrode surface against wear. However, this is subjected to polarity adapted in micro-EDM. Also, attachment/transfer of molten workpiece material to the electrode changes its status by way of release of electrode and related gap condition.

Uhlmann and Roehner (2008) investigated on the reduction of tool electrode wear in micro-EDM using novel electrode materials. The investigation results revealed that to minimise the wear of tool electrode, novel materials such as electrically conductive boron doped CVD diamond (B-CVD) and polycrystalline diamond (PCD) can be used. However, one has to look for the stability of the diamond wits spark erosion environment.

Yu et al. (2003) developed a simulation model for uniform wear method. The proposed method was based on one-dimensional wear model and predicted the longitudinal tool wear length. Bigot et al. (2005) investigated the suitability of electrode wear compensation methods, during the micro-EDM process. Electrode shape deformation and random variation of the volumetric wear were studied as the main factors and as an indicator for the achievable accuracy with the micro-EDM process. The measured wear ratio does not appear to be constant which does not allow for the use of compensation method.
Usage of suitable sensor for gap measurement, with necessary adaptive control technique can ensure sustained machining. Wang et al. (2009) experimentally investigated a wear-resistant electrode for micro-EDM. The results proved that Cu-ZrB$_2$ composite (copper-zirconium diboride) coated electrodes have better wear resistance than pure copper electrodes. They also found that it is feasible to use the wear compensation method on the basis of the difference between the wear ratio of matrix and that of coating material to maintain electrode shape precision. Aligiri et al. (2010) developed a new micro-EDM drilling method, in which the material removal volume is estimated as machining progresses. A real-time, material removal volume estimator is developed based on the theoretical electro-thermal model, number of discharge pulse and pulse discrimination system. The result showed that the proposed method is more reliable as compared to the uniform wear method. In drilling micro-holes of 900µm depth error can be reduced to 4% using the proposed method.

Tsai and Masuzawa (2004) evaluated the wear resistance of the electrode in micro-EDM. They found that the volumetric wear ratio of the electrode becomes small for the electrode material with high boiling point, high melting point, and high thermal conductivity. The result also showed W and Cu are good candidates for electrode.

Yan and Lin (2011) presented a novel multi-cut process planning method and a new electrode wear compensation method based on a machine vision system for three-dimensional (3D) micro-EDM. Experimental results indicated that the proposed multi-cut process planning and electrode wear compensation methods can improve machining time. Uhlmann et al. (2010) investigated the influence of grain size of the boron-doped CVD diamond coating on the wear behavior in micro-sinking EDM.
Experimental investigations showed that nanocrystalline coatings exhibit smaller discharge craters compared to those for microcrystalline diamond coatings. The microcrystalline coating also shows melted material around the discharge crater. However, it is subjected to further investigations.

In sum, the literature on TWR in micro-EDM emphasizes the need for wear compensation and associated adaptive control strategy.

2.3.3 Surface Roughness

Zhang et al. (2005) studied the roughness of the finished surface of AISI 1045 steel using copper as the electrode. The result revealed that surface roughness increases with an increase in the discharge voltage, discharge current and pulse duration. Ogun et al. (2004) investigated the various machining parameters which influence the surface profile of 2080 tool steel. It is found that surface roughness increases with increase in discharge current, pulse duration and dielectric flushing pressure.

While studying the molecular dynamics simulation of the material removal mechanism in micro-EDM, Yang et al. (2011) observed that the existence of micro pores in the workpiece material increases the depth of the discharge crater and melted area which results in the increase of machining surface roughness.

In micro-EDM, the machined surface is covered with many craters, micro-cracks and heat affected zones (HAZ) that are generated by sparks. The machined surface is covered by a multitude of overlapping craters whose geometry depends on the process parameters used, the physical properties of the electrodes, and the type of dielectric medium (Kurnia et al. 2009). Nakaoku et al. (2007) experimented with the micro-EDM of sintered diamond (SD) and found that the surface roughness of SDs is sufficiently good for
micro mould applications and the surface property of SDs with large diamond particles is quite different from that of metals.

Kiran and Joshi (2007) developed a model based on the configuration of a single-spark cavity formed as a function of process parameters to predict surface roughness of micro-EDMed surfaces. Yeo et al. (2009b) machined zirconium-based bulk metallic glass using micro-EDM. They employed three different electrodes, tungsten rod electrode, copper and brass tube electrodes, to elucidate the effects of different machining conditions on the machined surface roughness, burr width and tool wear. The results showed that the surface roughness is reduced when lower input energy is used. Also, tungsten electrode outperforms other electrode materials in finish machining.

Jahan et al. (2011) investigated the feasibility of improving surface characteristics of carbide in fine-finish sinking and milling micro-EDM using graphite nano-powder-mixed dielectric. The experimental results proved that the fine-powder-mixed micro-EDM of WC-Co with the addition of semi-conductive graphite nano-powder in dielectric oil provides smooth and defect-free surface. This is due to more surface area being exposed to machining at improved machining stability.

Chung et al. (2009) investigated the micro-EDMed surface based on electro chemical dissolution using deionised water. The results showed that the inner surface of the hole can be finished successfully via electrochemical dissolution in deionised water. Normally, electro chemical dissolution needs an electrolyte. Hence, the role of deionised water in electrochemical dissolution requires better understanding. It is seen that the introduction of tool rotation results in effectively removing the resolidified/recast layer of the inner surface and facilitates better surface finish consequently.
2.3.4 Circularity Error/Overcut

Circularity error is the radial distance between the two concentric geometrical circles. Circularity is the measure of concentricity, associated with form/geometric accuracy. The circularity of spark machined holes is influenced by two types of electric sources, RC-type generator and transistor-type generator. It is proved from the experimental results that good surface finish and circularity is achieved by RC type generator (Jahan et al. 2009a). In micro-EDM drilling error occurs due to the vibration of the electrode high roundness (Ali et al. 2009). The surface finish and circularity are also influenced by the rotation of the electrode (Egashira et al. 2010).

During machining process, overcut occurs due to side erosion and removal of debris. Overcut is also one of the major parameters to be considered to evaluate the machining performance of die-sinking micro-EDM. Pradhan et al. (2009) observed from the experimental investigations that the peak current and pulse-on time used in the machining process influence the overcut of the machined micro-holes. Overcut increases due to the increase of gap voltage and gap width as the higher voltage allows breakdown of dielectric at a wide gap due to the higher electric field (Jahan et al. 2009a).

In EDM, the machined surface is covered with many craters, HAZ and even micro-cracks (Rajurkar et al. 2006). In the micro-EDM process, three layers are categorised on the surface of the machined component. Pandey and Jilani (1986) observed from the micro-EDM process that the transverse section of workpiece has three distinct zones: a) white layer, b) HAZ, and c) unaffected parent metal. The top surface contains a thin layer of spattered material which can easily be removed by flushing. Underneath the spattered material a thin layer called re-cast layer is formed due to the rapid cooling effect of dielectric and adheres to the machined surface. Recast layer
is extremely hard, brittle and porous and may contain micro cracks. The next layer is the HAZ which is affected due to the amount of heat conducted with the material. As in the case of welding, when adjoining the molten / solidified deposition, formation of HAZ occurs. In EDM also, the heat of machining and subsequent depth (based on thermal diffusibility) facilitates formation of HAZ. Rajurkar and Pandit (1984) studied the recast layer and HAZ of EDMed AISI 4130 steel and observed that the damaged layer is estimated to be about 30 - 100µm with pulse on time of 100 to 300µs.

2.3.5 Micro-Cracks

Panda (2012) studied the surface damage caused due to thermal stress during electrical discharge machining process and identified that the crack formation on the surface is based on the nature and magnitude of the stress developed. Ekmekci et al. (2009) studied the micro-hole machining of mould steel using tungsten carbide tool electrode and a hydrocarbon-based dielectric liquid. They observed that discharged pulse energies influence the surface and they identified crack formation by utilizing low pulse energies during machining. The crack density is inversely proportional to the thermal conductivity of the work material (Lee et al. 1992) and as the content of carbon within the white layer increases (transfer from dielectric liquid), surface crack intensity increases rapidly.

Tsai et al. (2003) experimented with the micro-hardness of EDMed surface using Cu electrode and Cu-Cr composite electrode. They found that Cu metal electrode shows higher micro-hardness than that of composite electrodes. They also observed that in Cu electrode, cracks and pores are present in the recast layer (attributable to rapid heat extraction). Patowari et al. (2010) machined C-40 grade steel with WC/Cu powder metallurgy electrodes. They observed relatively a few micro-cracks and an increase in hardness. The EDMed surface has a relatively high micro-hardness, which is
due to the migration of carbon from the oil dielectrics to the workpiece surface forming iron carbides in the white layer (Kruth et al. 1995).

Ekmekci et al. (2006) observed that the micro-cracks are associated with the increase of thermal stresses exceeding the ultimate tensile strength of the material. The significant causes of the thermal stress in the machined surface are the drastic heating and cooling rates and the non-uniform temperature distribution. They observed only minor cracks while using tungsten and silver tungsten electrodes rather than copper and copper tungsten. Therefore, they recommended that micro-cracks present on the machined surface should be minimized to improve its service life.

2.3.6 Heat Affected Zone (HAZ)

Extremely high temperature resulted (Das et al. 2003, Ekmekci et al. 2005a) in the formation of multi-layered HAZ, including a hardened layer that possesses high brittleness and reduced fatigue strength of the work-material. Shabgard et al. (2011b) studied the depth of HAZ in EDM of AISI H13 tool steel and observed that increase in pulse currents results in decrease of depth of HAZ. Payal et al. (2008) investigated the machining performance of micro-EDM of EN-31 tool steel using different electrodes such as copper, brass and graphite. Analysis revealed that graphite electrode shows volcanic eruption and cracks due to non-uniform distribution of heat on work surface. Moreover, graphite electrode exhibits deeper HAZ than brass and copper electrodes.

Shabgard et al. (2011a) predicted the white layer thickness and HAZ on AISI H13 tool steel using copper as an electrode of EDM process. A numerical model was developed and it was concluded that increase in pulse on-time shows increase in white layer thickness and depth of HAZ. Ekmekci et al. (2009) reported that when de-ionized water is used as dielectric fluid
only minimum amount of retained austenite phase and the intensity of micro
cracks are identified in the white layer of the plastic mould steel than with
kerosene as dielectric. It is possible that pickup of carbon can induce
brittleness /cracking, sulphur in kerosene can also cause damage in HAZ.

Kahng and Rajurkar (1977) analyzed the texture of eroded surface
and reported that the application of higher discharge energy results in deeper
HAZ and subsequently deeper cracks. Thao and Joshi (2008) identified the
area of HAZ around the micro-electrical discharge machined holes and
thereby reduced the micro-hardness of the bulk material around the hole.
However, presence of HAZ needs not bring down hardness, unless there is
any depletion of chemistry. Liu et al. (2005) studied the micro-EDMed high
nickel alloy micro-holes and reported that the overcut is identified around the
micro-holes. It may be due to side erosion / inadequate electrode stiffness. It
is seen that during micro-EDM process, there is a possibility to attain varying
size / geometry of holes varying HAZ characteristics and varied response to
MRR and texture depending on the types of electrode used and associated
machining conditions. Paul et al. (2012) also observed that smaller overcut
dimensions of crater can be identified with low energy discharge with a
decrease in MRR, during the micro-EDM process of \( \gamma \)-titanium aluminide
alloy using steel rod as electrode.

Ekmekci et al. (2005b) found that the pulse energy influences the
thickness of heat-damaged layer than the shape of the pulse forms. To attain
higher performance, it is necessary to overcome the problem of crack
formation. The topography of micro-electrical discharge machined surface
was investigated by electron microscope. The increased pulse duration also
allows more heat to sink into the workpiece and spread which results in
deeper HAZ (Garg et al. 2010).
Long et al. (2008) investigated the micro growth process and characteristics of deposited material in micro-EDM deposition. They found that the micro-EDM deposition process can be used to fabricate finer micro structure with thinner electrode. The results also showed that the deposited material has compact micro structure and bonds close to the workpiece, which can be used for withstanding compress.

Jahan et al. (2010) investigated the migration of different sources of materials to the machined surface during fine finishing micro-EDM of cemented tungsten carbide (WC-Co). They revealed that the major source of material transfer to both workpiece and electrode is the diffusion of carbon and that migration occurs more frequently at lower gap voltages due to lower spark gap and stationary tool electrode.

In sum, the literature survey shows that during micro-EDM process, there is a possibility of attaining global maximum of high MRR, good surface finish, low order dimensional overcut and wear. The presence of definite HAZ minimizes the hardness of bulk material around the hole.

### 2.4 OPTIMIZATION METHODS

#### 2.4.1 Taguchi Method

Taguchi method has been widely used in engineering analysis as it can optimize performance characteristics through the settings of process parameters and reduce the sensitivity of the system performance to sources of variation. It is a powerful tool to design a high quality system (Lin et al. 2009).

Bigot et al. (2005) proposed Taguchi method for machining parameters optimization. They investigated the optimization of machining
parameters for rough and fine machining in micro-EDM. Vijayaraj et al. (2009) experimentally investigated the micro-WEDM of Ti alloy and the process is optimized using Taguchi method. Their work revealed that the Taguchi method is a powerful approach used in design of experiment. The high quality of machining characteristics is achieved without increasing the operation cost.

Recently, the Taguchi method was widely employed in several industrial fields and research work. Lin et al. (2002) adapted the Taguchi method to obtain the optimal machining parameter of the electrical discharge machining process. Pradhan et al. (2009) studied the optimization of micro-EDM parameters for machining Ti-6Al-4V super alloy by using the Taguchi method for the responses of MRR, TWR, overcut (OC) and taper. They also identified optimal combination levels using ANOVA and S/N ratio graphs.

Prihandana et al. (2009) used the Taguchi method to identify the optimal process parameters to increase the material removal rate of dielectric fluid containing micro-powder in micro-EDM using an $L_{18}$ orthogonal array. Tosun et al. (2004) used the Taguchi method to explore the effects of MRR and kerf of wire electrical discharge machining. Their works revealed that the Taguchi method is a powerful approach used in design of experiment. Furthermore, the Taguchi method can be used to optimize only single performance characteristics. Hence, in order to optimize multiple performance characteristics, researchers used grey relational analysis as a suitable theory.

Mitra et al. (2011) studied the effect of different dielectric medium in micro-EDM of $\gamma$-titanium aluminide. They analyzed both in the absence (dry conditions) and in presence of dielectric (EDM Oil) and observed circular craters in both the conditions. Further investigation to find the most influencing factors using ANOVA revealed that capacitance of RC-Circuit contributes significantly to crater formation followed by pulse frequency.
2.4.2 Grey Relational Analysis

The grey relational analysis is a method for measuring the degree of approximation among the sequences using a grey relational grade. Theories of the grey relational analysis have attracted considerable interest among researchers. Many researchers have also examined the optimization of process parameters.

Somashekhar et al. (2009a) used a new approach for the optimization of the micro-WEDM process with multiple performance characteristics based on ANOVA with the grey relational analysis. Chiang and Chang (2006) applied the grey relational analysis to optimize the WEDM process with the multiple performance characteristics such as MRR and the minimum surface roughness.

Taguchi method coupled with grey relational analysis has a wide area of application in manufacturing processes and can solve multi-response optimization problem simultaneously. Datta et al. (2008), Esme Ugur (2010) and Natarajan and Arunachalam (2011) present the optimization of multiple performance characteristics using the Taguchi method and grey relational analysis. From this analysis, the optimal parameters in EDM of 304 stainless steel are identified and the improvements in performance characteristics found using grey relational analysis. Jung and Kwon (2010) also employed the Taguchi method and grey relational analysis to find the optimal machining parameters to satisfy the multiple characteristics of the EDM process. Shen et al. (2012) determined the optimal combination of the process parameters during EDM process of 1Cr17Ni7 using Cu as electrode using Taguchi-based grey relational analysis. From the analysis it is inferred that the performance of MRR, TWR and SR are improved. Muthukumar et al. (2010) identified the optimum levels of parameters by grey relational analysis and percentage
contribution of all the parameters by ANOVA to study the optimization of machining parameters.

Panda (2010) employed a new-hybrid approach of neuro-grey modeling (NGM) for modeling and optimization of multi-process attributes of electro-discharge machining process. The study proved that combining ANN and GRA in NGM is found to be suitable to provide generalized solution pertaining to parameter design of the process.

2.4.3 Artificial Neural Network (ANN)

An ANN can work satisfactorily as a knowledge-acquisition tool for diagnosis problems. Sarkar et al. (2010) presented an integrated approach for optimization of wire EDM of gamma titanium aluminide (γ-TiAl) with the assistance of ANN modeling. Aravind et al. (2009) attempted to model the MEDM process for MRR using ANN. Experiments were performed for all possible combinations with three levels using design of experiments considering voltage, capacitance, feed and speed of the electrode as input parameters and MRR as output parameter. Somashekhar et al. (2009b) proposed an ANN model to represent the relationship between MRR, overcut and input parameters of micro- wire electro discharge machining (WEDM) process. The results showed that a well-trained ANN system is very helpful in estimating performance characteristics.

Pellicer et al. (2009) investigated the influence of different process parameters and tool electrode shape on performance measures for copper electrode and AISI H13 steel workpiece in sinking type micro-EDM process. They used advanced process models using ANNs to obtain a better process-prediction. Ramakrishnan and Karunamoorthy (2008) developed ANN models and multi-response optimization techniques to predict and select the best cutting parameters of WEDM process. Somashekhar et al. (2010)
analyzed the material removal of micro-EDM using ANN. They developed a neural network model using MATLAB programming and the trained neural network is simulated. They also employed genetic algorithms (GAs) to determine optimum process parameters for any desired output value of machining characteristics. Experimental results showed that the process optimization through ANN modeling and GA technique is very effective in optimizing the performance of the micro-EDM process.

Suganthi et al. (2013) proposed adaptive neuro-fuzzy inference system (ANFIS) and back propagation (BP) based artificial neural network (ANN) models for the prediction of multiple quality responses in micro-EDM operations. They found that the predicted values of the responses are in good agreement with the experimental values and they also observed that the ANFIS model outperforms the BP-based ANN.

To evaluate the effect of machining parameters on performance characteristics, a specially designed experimental procedure is required. Classical experimental design methods are too complex and difficult to use. Additionally, a large number of experiments have to be carried out when the number of machining parameters increases (Lin 2002, Yang and Tarng 1998). The increased pulse duration allows more heat to sink into the workpiece and spread which results in deeper HAZ.

2.4.4 Mathematical Modeling

Kurnia et al. (2008) predicted process performance measures in micro-electrical discharge machining such as MRR, TWR and SR. They proposed a theoretical model to analyze the approximation of performance measures based on the crater prediction. The results of comparison between analytical and experimental data of MRR and TWR revealed a variation of up to 30% and 24% respectively. Luis et al. (2005) studied the influence of MRR
and electrode wear in the die-sinking EDM of siliconized silicon carbide. To achieve this, design of experiments (DOE) and multiple linear regression statistical techniques were employed. Dhar et al. (2007) employed a second order non-linear mathematical model to evaluate the effect of current, pulse-on time and air gap voltage on MRR, TWR, radial overcut (ROC) on electrical discharge machining of Al-4Cu-6Si alloy-10wt% SiCp composites. They revealed that MRR, TWR and ROC increase significantly with the increase of current and pulse duration. Moreover, gap voltage shows minimum influence on the three responses. George et al. (2004) studied the most important input parameter of EDMed carbon-carbon composite using regression models and response surfaces method and identified spark current as the most influencing factor. Shabgard and Shotorbani (2010) developed mathematical models for relating, TWR and SR to machining parameters such as current, pulse-on time and voltage.

Bhattacharyya et al. (2007) analyzed the influences of major machining parameters such as peak current and pulse-on duration on different materials machined through EDM. They employed mathematical models based on response surface methodology (RSM) and found that the lower peak current and pulse-on duration shows minimum SR and white layer thickness. Pradhan et al. (2008) used RSM to identify the influencing parameter on MRR in EDM process of AISI D2 tool steel with copper electrode. Dav et al. (2012) developed an empirical model using linear regression analysis by applying logarithmic data transformation of non-linear equation to predict MRR during the EDM of Inconel 718.
2.5 SUMMARY

The following observations can be drawn from the detailed literature review as the bases of this research.

Micro-EDM has some distinct characteristics and the literature review has established clear techniques/strategy for achieving higher MRR and lower TWR. In addition to extending the wide applications of micro-EDM, it is desirable to have a better surface finish. In die-sinking micro-EDM, maximum MRR, minimum TWR and better surface finish can be achieved based on the properties of the electrodes used.

The literature survey clearly indicated the need for selection of proper dielectric, electrode material and even current source for achieving desired results in EDM, especially in micro-EDM.

The literature has presented the influence of various dielectrics. Both de-ionized and paraffin exerts their influence. With regard to electrode, copper, graphite, tungsten-based electrodes have been tried out. The result showed that material specific electrodes are to be selected for desired results.

Various research works have been carried out with different workpiece materials such as tool steels, ceramics, composites, tungsten and titanium alloys. However, in micro-EDM process EN24 die steel with a wide range of applications in die and mould making has not been studied much.

From the available literature it can be seen that the optimization and modeling of MRR, TWR and SR for different electrodes has not been reported yet. Therefore, there is an urgent need for performance analysis of various electrodes on EN24 die steel to produce quality micro-holes. The major challenges of die-sinking micro-EDM were identified and the research
problem was formulated. The objectives of this work were also outlined. Based on the objectives, the research methodology was sketched out. Based on the proposed methodology, the experimental procedure is discussed in the next chapter.