2.1 STATE OF THE ART IN SINK-EDM PROCESS

To gain a full appreciation of the state of the art in sink-EDM process, 159+ research papers on the subject were read and analyzed. To appropriately summarize the papers and apply them to the research intended for this study, the same six questions were asked of each paper. What is the definition of sink-EDM process? What are the strengths and weaknesses of the sink-EDM process? What types of parts are being machined by sink-EDM process and in what materials are they being machined? What is the minimum feature size being machined? How quickly are the parts being made or what is the machining rate? What is the unique aspect of the research that improves the sink-EDM process? Every paper does not have an answer to every question, and often times the answers are a bit contradictory.

However, almost all of the papers agree on the second question. The main strength of the sink-EDM process is its unique feature of using thermal energy which renders the ability to machine geometrically complex shapes into any electrically conductive advanced exotic engineering materials that are extremely difficult-to-machine by conventional machining processes, with very low forces. In EDM process the forces are very small
eliminating mechanical stresses, chatter and vibration problems during machining, because there is no direct contact between the tool electrode and the workpiece. There are two very important weaknesses to the sink-EDM process. The first weakness is that material removal rate is rather low compared to other machining processes. The second weakness is that while the workpiece is being machined, the tool electrode also wears at a rather significant rate. This tool-wear leads to shape inaccuracies.

The results of all the research papers on sink-EDM process have similar answers to the strengths/weaknesses. In recent years, EDM researchers have explored a number of ways to improve the sparking efficiency including some unique experimental concepts that depart from the EDM traditional sparking phenomenon. Despite a range of different approaches, this new research shares the same objectives of achieving more efficient metal removal coupled with a reduction in tool wear and improved surface quality.

This chapter discusses the research work in sections and subsections carried out from the inception to the development of sink-EDM within the past decade. It reports on the EDM research relating to improving performance measures, optimizing the process variables, monitoring and control the sparking process, simplifying the electrode design and manufacture. A range of EDM applications are highlighted together with the development of hybrid machining processes. The final
part of the chapter discusses these developments and outlines the trends for future EDM research.

2.2 APPLICATIONS OF EDM PROCESS

This section discusses some of the applications of EDM commonly found in the industry. It also includes other experimental interests providing a feasible expansion of EDM applications.

2.2.1 Materials with Heat Treatment

In some applications, EDM has replaced traditional machining processes such as the milling of heat-treated tool steels. Milled material has to be within an acceptable hardness range of less than 30–35 HRC with ordinary cutting tools. Bayramoglu and Duffill [28]. However, EDM allows tool steels to be treated to full hardness before machining, avoiding the problems of dimensional variability, which are characteristic of post-treatment. Arthur, et. al., [29]

Since EDM does not induce mechanical stresses during machining, it provides an additional advantage in the manufacture of intricate products. Weng and Her [30] carried out several successful experiments involving an electrode of 50 μm diameter and a multi-electrode for the batch production of micro-parts. The proposed method significantly reduces the production time and costs of fabricating both the electrodes and parts.
2.2.2 EDM Process for Micro-Machining

The recent trend in reducing the size of products has given micro-EDM a significant amount of research attention. Micro-EDM is capable of machining not only micro-holes and micro-shafts as small as 5 μm in diameter but also complex three-dimensional (3D) micro cavities. Rajurkar and Yu [31] this is unlike mechanical drilling, which can produce holes just up to 70 μm, or the micro-fabrication process such as laser machining, which can only create holes of 40 μm. Masuzawa [32]. Masuzawa, et. al., [33–35], also made several successful attempts producing micro parts such as micro-pins, micro-nozzles and micro-cavities using micro-EDM. In addition, a feasibility study of applying micro-EDM as an alternative method for producing photo-masks used in the Integrated Circuit (IC) industry has been conducted. Yeo and Yap [36]

Other applications include the general interest in developing trajectory EDM to solve the machining problems of water-cooling channels used in moulds or manifolds. Ishida and Takeuchi [37] recently proposed a trajectory EDM technique facilitating the electrode to move along a smooth trajectory, while performing EDM eliminating the conventional drilling or boring operation required. Other attempts have also been made on trajectory EDM but special apparatus or complex control mechanism is needed to develop the trajectory motion of electrode. Fukui, et. al., and Ichiyasu, et. al., [38, 39]
2.2.3 Ceramics as Engineering Material

The EDM of advanced ceramics has been widely accepted by the metal cutting industry owing to the competitive machining costs and features. There are different grades of engineering ceramics, which Konig, et. al., [11], classified as non-conductor, natural-conductor and conductor (a result of doping non-conductors with conductive elements). Sanchez, et. al., [40] provided a literature survey on the EDM of advanced ceramics, which have been commonly machined by USM and LBM. In the same paper, they proved the feasibility of machining boron carbide (B₄C) and silicon infiltrated silicon carbide (SiSiC) using EDM and WEDM. A HMP combining USM and EDM was also experimented to enhance the dielectric circulation in the spark gap, when machining engineering ceramics with significant improvement in the performance measures and reduction in the thickness of the white layer. Lee, et. al., [41]

In recent years, the use of EDM for ceramics has overcome the technological limitation of the process requiring the electrical resistance of material with threshold values of approximately 100 [20] or 300 Ω/cm. Firestone [42]. Mohri, et. al., [43] brought a new perspective to this traditional EDM phenomenon by using an assisting electrode facilitating the sparking of insulating ceramics. Both EDM and WEDM have been successfully tested for diffusing conductive particles from assisting electrodes onto the surface of Sialon ceramics or silicon nitride (Si₃N₄). Other types of insulating ceramics materials including oxide ceramics such
as zirconia (ZrO₂) and alumina (Al₂O₃), which have very limiting electrical conductive properties have also been examined based on the same technique. Mohri, et. al., [44]. On the other hand, Matsuo and Oshima [45] investigated the EDM of ZrO₂ and Al₂O₃ by doping with carbide (NbC or TiC), thereby increasing the electrical conductivity of the materials.

2.2.4 Modern Composite Materials

The development of different modern composite materials in the last decade has led to an expansion of EDM applications. Yan, et. al., [46] surveyed the various machining processes performed on Metal Matrix Composites (MMC) and experimented with the machining of Al₂O₃/6061Al composite using rotary EDM coupled with a disc-like electrode. The feasibility of machining ceramic–metal composite steel plate coated with WC–Co (tungsten carbide–cobalt) using plasma spraying was also examined. Mamalis, et. al., [47]. The coating of WC–Co onto parts by means of plasma spraying is used extensively in the automobile and aerospace industry to prevent erosion and wear. Muller and Monaghan [48] compared the EDM of Particle Reinforced Metal Matrix Composite (PRMMC) with other non-conventional machining processes such as LBM and abrasive water jet (AWJ). It was found that EDM was suitable for machining PRMMC with a relatively small amount of sub-surface damage but the MRR was very slow.
2.3 MAJOR AREAS OF EDM RESEARCH

In this section, the major research areas in EDM are arranged under three headings. The first relates to machining performance measures such as Material Removal Rate (MRR), Tool Wear Rate (TWR) and Surface Quality (SQ) and also surveys them. The second area describes the effects of process parameters including electrical and non-electrical variables, which are required to optimize the stochastic nature of the sparking process on the performance measures. Finally, research concerning the design and manufacture of electrodes is reported.

2.3.1 Performance Measures in EDM Process

A significant number of papers have been focused on ways of yielding optimal EDM performance measures of high Material Removal Rate (MRR), Low Tool Wear Rate (TWR) and Satisfactory Surface Quality (SQ). This section provides a study into each of the performance measures and the methods for their improvement.

2.3.1.1 Material Removal Rate (MRR)

(i) Material Removal Mechanism

Several researches have explained the Material Removal Mechanism (MRM) in terms of the migration of material elements between the workpiece and electrode. Soni and Chakraverti [49] showed an appreciable
amount of elements diffusing from the electrode to the workpiece and vice versa. These elements are transported in solid, liquid or gaseous state and alloyed with the contacting surface by undergoing a solid, molten or gaseous-phase reaction. Roethel, et. al., [50]. The types of eroded electrode and workpiece elements together with the disintegrated products of dielectric fluid significantly affect the MRM relating to the three phases of sparking, namely breakdown, discharge and erosion. Erden [51]. In addition, reversing the polarity of sparking alters the material removal phenomenon with an appreciable amount of electrode material depositing on the workpiece surface. Gangadhar, et. al., [52]

Other ways of explaining the MRM have also been reported by different authors. Singh and Ghosh [53] showed that the electrostatic forces and stress distribution acting on the cathode electrode were the major causes of metal removal for short pulses. Gadalla and Tsai [54] attributed the material removal of WC–Co composite to the melting and evaporation of disintegrated Co followed by the dislodging of WC grains, which have a lower electrical conductivity. However, Lee and Lau [55] argued that thermal spelling also contributes to the MRM during the sparking of composite ceramics due to the physical and mechanical properties promoting abrupt temperature gradients from normal melting and evaporation.
(ii) Methods of Improving Material Removal Rate

The application of CNC to EDM has helped to explore the possibility of using alternative types of tooling to improve the MRR. EDM commonly employs 3D profile electrodes, which are costly and time-consuming to manufacture for the sparking process. However, experimental work has been performed with a frame electrode generating linear and circular swept surfaces by means of controlling the electrode axial motion. Bayramoglu and Duffill [56]. A similar machining technique using a wire frame electrode was conducted to compare the time taken to machine a cubic cavity using a 3D solid electrode. Saito, et. al., [57]. These techniques eliminate the need to utilise the 3D electrode to perform the roughing operation by replacing the simple electrode to remove unwanted material in a complete block improving the machining efficiency and MRR.

EDM has further exploited the capability of CNC in providing multi-axis movements for simple electrodes producing complex 3D shape parts. Kaneko and Tsuchiya [58] successfully experimented and investigated the machining characteristics of contour machining with simple cylindrical electrodes. Bleys, et. al., [59] referred the novel machining technique to milling-EDM (MEDM), which eliminates the need of producing and storing various types of 3D electrodes for different kinds of workpiece shapes. Wong and Noble [60] introduced more complex motions to the cylindrical electrode by using a micro-computer controlled XY table.
Another promising MRR improvement technique has also been made recently by modifying the basic principle of EDM, which only delivers single discharge for each electrical pulse. Kunieda and Muto [61] experimented on a multi-electrode discharging system delivering additional discharge simultaneously from a corresponding electrode connected serially. The design of electrode Mohri, et. al., [62] was based on the concept of dividing an electrode into multiple electrodes, which are electrically insulated. The TWR and energy efficiency were claimed to be better than the conventional EDM without any significant difference in the Surface Roughness (SR). An oxygen assisted EDM system, which greatly improves the MRR was tested also by supplying oxygen into the discharge gap. Kunieda, et. al., [63]

2.3.1.2 Tool Wear Rate (TWR)

(i) Tool Wear Process

The Tool Wear Process (TWP) is quite similar to the MRM as the tool and workpiece are considered as a set of electrodes in EDM. Mohri, et. al., [64] claimed that tool wear is affected by the precipitation of carbon from the hydrocarbon dielectric onto the electrode surface during sparking. They also argued that the rapid wear on the electrode edge was due to the failure of carbon to precipitate at difficult-to-reach regions of the electrode.

From this simple understanding of TWP, some useful applications exploiting both the advantages and disadvantages of electrode wear have
been developed. Marafona and Wykes [65] introduced a wear inhibitor carbon layer on the electrode surface by adjusting the settings of the process parameters prior to normal EDM conditions. Although the thickness of the carbon inhibitor layer made a significant improvement on the TWR, it has little effect on the MRR. On the other hand, for applications requiring material accretion, a large pulse current is encouraged to increase electrode wear implanting electrode material onto the workpiece. Mohri, et. al., [66]

(ii) Methods of Improving Tool Wear Rate

The orbiting of the electrode relative to the workpiece is the most common machining strategy of compensating the tool wear. It involves the electrode making a planetary motion producing an effective flushing action, which improves the part accuracy and process efficiency. Snoeys, et. al., [67]. The orbiting technique also reduces the number of different electrodes required for initial roughing and final finishing operations. In order to optimize the electrode trajectory in real-time, a computer integrated planetary machining strategy based on continuous adaptation of machining parameters was developed. Staelens and Kruth [68]

Similar tool wear compensation strategies have also been applied to MEDM, which is commonly executed in thin layers using simple cylindrical or tubular electrodes. Yu, et. al., [35] introduced a uniform tool wear machining method compensating the longitudinal tool wear by applying an overlapping to-and-fro machining motion. Bleys, et. al., [59] initially
evaluated the reduction of tool length based on pulse analysis and subsequently compensated the tool wear by controlling the machining downward feeding movement in real-time. Dauw and Snoeys [69] derived the measurement of tool wear from the study of pulse characteristics based on discharge voltage fall time. On the other hand, Kunieda, et. al., [70] reduced the tool wear ratio by performing MEDM using high velocity gas as the dielectric medium.

The different methods of simulating the EDM process also provide a good opportunity of understanding and compensating the tool wear. Dauw [71] developed a geometrical simulation of EDM illustrating the development of tool wear and part geometry. It is also considered as an off-line process planning technique as the simulation algorithm is largely based on MRR, TWR and spark gap. However, the simulation of discharge location and spark gap, which are dependent on the distribution of debris concentration, was reported to yield a more realistic representation of the sparking phenomenon. Kunieda and Kiyohara [72]. Other methods include a reverse simulation of EDM obtaining the shape of the electrode based on the desired workpiece shape. Kunieda, et. al., [73]

2.3.1.3 Surface Quality

(i) Surface Quality Analysis

The electrical discharge machined (EDMed) surface is made up of three distinctive layers consisting of white layer/recast layer, Heat Affected Zone
(HAZ) and unaffected parent metal [25, 26]. Lim, et. al., [74] provided a review on the metallurgy of EDMed surface, which is dependent on the solidification behavior of molten metal after the discharge cessation and subsequent phase transformation. The thickness of the recast layer formed on the workpiece surface and the level of thermal damage suffered by the electrode can be determined by analyzing the growth of the plasma channel during sparking. Pandey and Jilani [75]

Since the white layer is the topmost layer exposed to the environment, it exerts a great influence on the surface properties of the workpiece. Several authors discovered the presence of micro-cracks and high tensile residual stresses on the EDMed surface caused by the high temperature gradient. Lin, et. al., [76]. The adverse effect of discharge energy also provided some insights on the fatigue strength of the workpiece, which propagates from the multiple surface imperfections within the recast layer. Abu Zeid [77].

In addition, the EDMed surface has a relatively high micro-hardness, which can be explained by the emigration of carbon from the oil dielectrics to the workpiece surface forming iron carbides in the white layer Kruth, et. al., [78]. The concentration of carbides, both as surface layer on the workpiece and as fine powder debris, is dependent on the frequency and polarity of the applied current together with other processing parameters such as pulse shape, gap spacing and dielectrics temperature Ayers and Moore [79]. However, Thomson [80] argued that the pulse duration and
type of electrode material under a paraffin dielectric has little effect on the amount of carbon contamination. Thomson also suggested that the number and size of micro-cracks increase with pulse duration when machining with copper electrode.

(ii) Methods of Improving Surface Quality

a) Surface alloying

The surface alloying method using the composite electrode to improve the surface properties of the workpiece has been reported by a number of authors [81-84]. The composite electrode is also referred to as the green compact, sintered or Powder Metallurgy (PM) electrode. It has low thermal conductivity allowing the composite material to disintegrate from the electrode and alloy onto the workpiece surface producing less cracks, high corrosion and wear resistance. Simao, et. al., [85] provided a review on the PM electrode and identified the effect of various operating parameters on achieving the desired workpiece surface characteristics.

b) Ball burnish machining

In addition, the feasibility studies of using EDM with Ball Burnish Machining (BEDM) have been experimented to improve the workpiece surface integrity. BEDM uses hard smooth balls attached to the electrode to form a plastic deformation layer on the workpiece surface during sparking yielding a hardened and modified surface micro-structure. Samuel, et. al., and
Simao, et. al., [86, 87]. It also improves the corrosion resistance, fatigue strength and surface roughness of the workpiece surface, Loh, et. al., [88, 89]. Yan, et. al., [90] applied rotary motion to BEDM which further improves the MRR and SR when compared to conventional EDM.

c) Powder addictives

Lately, powders are suspended in the dielectric fluid as another means of improving the surface properties. The powder particles facilitate the ignition process by creating a higher discharge probability and lowering the breakdown strength of the insulating dielectric fluid. Schumacher [91]. As a result, it increases the MRR, reduces the TWR and improves the sparking efficiency producing a strong corrosion resistant EDMed surface [92, 94]. Moreover, the presence of powders in the dielectric fluid increases the micro-hardness and reduces the micro-cracks on the EDMed surface due to a reduction of losing alloying elements residing onto the workpiece. Quan and Liu [95]. Luo [98] reported an improvement in machining stability and discharge transitivity during EDM due to a decline in arcing frequency contributed by the even distribution of gap debris.

d) Surface finish simulation

In the past few decades, a few EDM modeling tools correlating the process variables and surface finish have been developed. Tsai and Wang [96] established several surface finish models based on various neural-networks taking the effects of electrode polarity into account. They
subsequently developed a semi-empirical model, which is dependent on the thermal, physical and electrical properties of the workpiece and electrode together with pertinent process parameters. It was noted that the later model produces a more reliable surface finish prediction for a given work under different process conditions. Tsai and Wang [97]. Jeswani [98] studied the effects of workpiece and electrode materials on SR and suggested an empirical model, which focused solely on pulse energy, whereas Zhang, et. al., [99] proposed an empirical model, built on both peak current and pulse duration, for the machining of ceramics. It was realized that the discharge current has a greater effect on the MRR while the pulse-on time has more influence on the SR and white layer.

2.3.2 Effect of Process Parameters in EDM

This section focuses on the effect of process parameters such as electrical and non-electrical parameters on the various performance measures.

2.3.2.1 Effect of Electrical Parameters

The stochastic thermal nature of the EDM process makes it difficult to explain experimentally all the effects of electrical parameters on the individual performance measures. Thus, this section describes research in the areas of optimization, monitoring and control of the various electrical parameters on the performance measures.
(i) Parameter optimization

Traditionally, the selection of the most favorable process parameters was based on experience or handbook values, which produced inconsistent machining performance. However, the optimization of parameters now relies on process analysis to identify the effect of operating variables on achieving the desired machining characteristics. Lin, et. al., [100] employed grey relational analysis for solving the complicated interrelationships between process parameters and the multiple performance measures of the EDM process.

Other works have applied the Taguchi approach to analyze and design the ideal EDM process. Marafona and Wykes [65] used the Taguchi method to improve the TWR by introducing high carbon content to the electrode prior to the normal sparking process. Lin, et. al., [101] employed it with a set of fuzzy logic to optimize the process parameters taking the various performance measures into consideration. Tzeng and Chen [102] optimized the high-speed EDM process by making use of dynamic signal-to-noise (S/N) ratio to classify the process variables into input signal, control and noise factors generating a dynamic range of output responses.

(ii) Process Monitoring and Control

a) Pulse parameters

The real-time monitoring and control of EDM process has often been built on the identification of different pulses. EDM pulses can be classified into
open, spark, arc, off or short pulses, which are dependent on the ignition delay time, and have a direct influence on the MRR, SR and accuracy of the part. Cogun [103]. Therefore, the recognition and classification of the different pulses provide a viable option of monitoring and controlling the sparking process by measuring the related gap voltage and current. Kao and Tarng [104] proposed a neutral-network method, while Liu and Tarng [105] suggested an network method of classifying and regulating the EDM pulses occurring at varying machining conditions. Weck and Dehmer [106] studied the effect of different pulses on MRR together with TWR and developed an adaptive gap controller, which reduces the number of undesirable pulses.

b) Time domain

However, several authors [107–109] argued that the gap voltage is not a good indicator of the dynamic responses taking place at the spark gap largely due to the High Frequency (HF) noise component. These authors instead suggested monitoring the time ratio of transient arc measured by the pulse-on time, which shows the trend towards undesirable arcing. Yu, et. al., [110] also studied the time domain of different pulses and presented a wavelet transform serving as an input signal for an online monitoring and control systems. Wang, et. al., [111] measured the various transient pulses and regulated the cycle time of periodical retraction (auto-jumping) of electrode avoiding arcing damage and machining instability during sparking process. A self-tuning regulator for an EDM servo control system, which
directly adjusts the servo feed rate based on the discharge time ratios from
the gap has also been reported. Rajurkar, et. al., [112]

c) Fuzzy logic

The application of fuzzy logic to the adaptive control system provides a
reliable pulse discriminating role during the EDM process. Several authors
claimed that the fuzzy logic control implements a control strategy that is
adopted by a skilled operator to maintain the desired machining process
Boccadoro and Dauw [113]. Tarng, et. al., [114] suggested a fuzzy pulse
discriminator established on the linguistic rules acquired from the
knowledge of experts and expressed mathematically through the theory of
fuzzy sets. However, the definition of membership functions for each fuzzy
set is not straightforward and is based on exploratory means to classify
various discharge pulses. Tarng and Jang [115] shortly proposed the use of
Genetic Algorithms (GAs) to synthesize the required membership functions
automatically.

d) Radio frequency

In addition, the emitted Radio Frequency (RF) or HF signal generated
during EDM has been used to monitor and control the sparking process.
Bhattacharyya and El-Menshawy [116,117] developed an RF monitoring
system providing a pulse control to the machine power generator by
examining the RF signal created from the spark gap. The RF monitoring
system detects any drop in the intensity of signals to a threshold value
whenever the discharge changes from sparking to arcing. Rajurkar and Wang [118] provided a good review on the research and development of advanced monitoring and control systems.

### 2.3.2.2 Effect of Non-Electrical Parameters

Besides electrical parameters, non-electrical parameters such as the flushing of dielectric fluid together with the rotational movement of the workpiece and electrode also play a critical role in delivering optimal performance measures. This section discusses the effects of non-electrical parameters on the various performance measures.

#### (i) Flushing of dielectric fluid

The flushing of the dielectric during the sparking process has an adverse effect on the EDM performance measures. Lonardo and Bruzzone [119] revealed that flushing during the roughing operation affected the MRR and TWR, while in the finishing operation, it influenced the SR. The flushing rate also influences the crack density and recast layer, which can be minimized by obtaining an optimal flushing rate. Wong, et. al., [120]. In addition, the different properties of the dielectric fluid also play a vital role in flushing away the debris from the machining gap. Tool wear and MRR are dependent on the breakdown resistance, conductivity, viscosity, flash point, health and safety factors of dielectric fluids, [121]. The possibility of using water instead of kerosene as the working fluid for micro-EDM has been
experimented. Kagaya, et. al., [122]. The result revealed a high MRR and low TWR without any metal carbides forming on the workpiece surface. Benedict [123] broadly classified the most common flushing methods delivered under constant pressure into five main categories. The dielectrics can be delivered down or up through the electrode, by means of vacuum flow, vibration or jet flushing. A dynamic jet flushing with moving nozzles that sweep along the sparking gap providing an even distribution of debris concentration has been reported recently. Masuzawa, et. al., [124]. Other alternative ways of improving the flushing condition involve making relative motion between tool and workpiece. These include making an electrode planetary movement at the lateral gap allowing dielectrics to flow in from one side and leave at the other side of workpiece. Masuzawa, et. al., [125]. Several authors Bruijin, et. al., [126] applied magnetic fields to transport magnetic debris through the gap while, others Enache, et. al., [127] used controlled forced vibration to evacuate debris effectively from the sparking gap. The application of ultrasonic vibration on both electrodes facilitating an induced flushing within the gap has also been evaluated. Murti and Philip [128]

(ii) Rotating the workpiece

Besides the flushing of the dielectric, the techniques of applying rotational motion to the sparking process also affect the EDM performance. Guu and Hocheng [129] provided a workpiece rotary motion to improve the circulation of the dielectric fluid in the spark gap and temperature
distribution of the workpiece yielding better MRR and SR. On the other hand, Kunieda and Masuzawa [130] proposed a horizontal EDM (HEDM) process in which the main machining axis is horizontal instead of the conventional vertical axis. The change in the basic construction in addition to the rotary motion of the workpiece offered an accessible evacuation of debris improving the erosion efficiency and accuracy of the sparking process. HEDM has also been experimented in the micro-machining of small parts. Masuzawa, et. al., and Mohri, et. al., [131,132]

(iii) Rotating the electrode

Similarly, the rotary motion has been introduced to the electrode to improve the performance measures of the EDM process. It serves as an effective gap flushing technique, which significantly improves the MRR and surface roughness. Sato, et. al., [133]. The same alloying effect of migrating material elements from the workpiece and tool is also observed, in relation to the morphology, chemical composition and size distribution of debris, when using rotating electrodes. Soni [134]. Soni and Chakraverti [135] compared the various performance measures of rotating electrode with the stationary electrode. The results showed an improvement in MRR due to the better flushing action and sparking efficiency with little tool wear but the surface roughness was high. On the other hand, Enache [136] studied the effects of the controlled force vibration introduced to the electrode on the various performance measures. It was found that the vibratory motion yields comparable effects as the rotary motion of electrode improving the
MRR, enhancing the surface quality of workpiece and increasing the stability of machining process.

2.3.3 Tool Electrode Design and Manufacture

This section describes the different computer-aided systems that have been experimentally implemented in the design of the electrode. The major research interest in the production of electrodes using the rapid prototyping technique is also included in the section.

2.3.3.1 Computer Assisted Tool Electrode Design

The design and manufacture of an electrode has progressed along with the technological advancement made in the various computer-aided systems. A CAD system is capable of creating the electrode and holder designs from the workpiece 3D geometry and identifying any undesirable sharp corners on the designs, which are difficult to produce, by measuring the surface angle along the edges. Ding, et. al., [137]. The recent development in CAD/CAM systems and communications controls has also provided a thorough integration towards the design and manufacture of electrodes by selecting essential machining parameters prior to the machining operation. Kruth and Peters [138]. A Computer-Aided Process Planning (CAPP) system for electrode design has also been built using feature-based workpiece description. Lauwers and Kruth [139]. In view of the growing concern for green manufacturing, Yeo and New [140] developed an
environmentally friendly process planning system using a multi-objective analysis for the EDM process. The system takes both the environment impact, such as process energy and waste, and traditional manufacturing measures, such as production rate and quality, into account when performing the process planning. DeVries, et. al., [141] suggested the integration of EDM within the Computer Integrated Manufacturing (CIM) environment. However, DeVries stated that the large inconsistencies in the way the EDM process parameters and generator settings were programmed have hindered the standardization and integration within the CIM environment.

2.3.3.2 Rapid Tooling Manufacture

A number of research works have explored the application of Rapid Prototyping (RP) techniques in the production of electrode. The various routes of manufacturing the Rapid Tooling (RT) electrode are classified as either the direct or indirect approach. Arthur, et. al., [29]. The direct manufacturing route uses a PR (positive/male) model, while the indirect route uses RP (negative/female) cavity as an immediate step to machine the RT electrode. The direct laser sintering of metal powders for the manufacture of the RT electrode, which is subsequently electro less copper and copper electroplated to improve the surface finish and conductivity of the sintered electrode has been studied. Tay and Haider [142]. The performance of sintered copper electrodes is comparable to that of solid copper electrode but the dimensional accuracy of the former electrode
during electroplating was inconsistent affecting the accuracy of the part produced. Yang and Leu [143] experimented the indirect technique of generating mould cavities and RT electrodes by electroforming of RP masters. However, the thermal deformations caused by the removal of metal shell from RP master and backfilling of electroformed metal shell with molten metal are the major sources of inaccuracy in producing the RT electrode. Despite the unsatisfactory performance of the RT electrode, the potential of manufacturing it using RP technology can still be proven to be a viable option when a better understanding of the various failure modes is recognized. Arthur and Dickens [144] noted that the RT electrodes generate greater heat at higher MRR resulting in a combination of delamination, thinning and distortion of electrodes. They suggested measuring the thermal condition within the electrode so that the machining process could be optimized thereby improving the performance of PR electrode. On the other hand, Durr, et. al., [145] studied the effects of porosity on the wear and erosion behavior of RT electrodes. They proposed a subsequent treatment of RT electrodes by infiltration with silver containing brazing metal minimizing the porosity and improving the performance of the sintered electrode.
2.4 TRENDES OF THE FUTURE EDM RESEARCH

The numerous EDM research interests referred in this chapter have been classified into four different major areas. The classification in this section is used to discuss the various research areas and possible future research directions.

2.4.1 Optimizing the Process Parameters

The EDM process has a very strong stochastic nature due to the complicated discharge mechanisms. Pandit and Mueller [146] making it difficult to optimize the sparking process. The optimization of the process often involves relating the various process variables with the performance measures maximizing the MRR, while minimizing the TWR and yielding the desired SR. In several cases, S/N ratios together with the Analysis of Variance (ANOVA) techniques are used to measure the amount of deviation from the desired performance measures and identify the crucial process variables affecting the process responses.

The process variables include not only the electrical but also non-electrical parameters, which have received quite a substantial amount of research interest. As discussed earlier, these research works explored new and different ways of delivering a more efficient and stabilized sparking process improving the commonly observed performance measures. In addition, the feasibility of manufacturing the electrode using the RP technique has been extensively studied to improve the performance of
tools and sparking. Therefore, with the continuous research effort made in understanding the initialization and development of sparking process, the different means of optimizing the various process variables will continue to be a major area of further development reducing the stochastic sparking characteristic.

2.4.2 Monitoring and Control of the Process

The monitoring and control of the EDM process are often based on the identification and regulation of adverse arcing occurring during the sparking process. Most of the approaches measure pulse and time domain parameters to differentiate the arc pulses from the rest of EDM pulses. The option of using emitted RF has also been experimented but generates very little research interest. As for the adaptive control system, it mainly relies on the application of fuzzy logic to maintain the machining process. The fuzzy logic provides a control strategy that is equivalent to the expertise and experience of a skilled operator. However, it is not easy to establish the pulse discriminating function, which is based on trail-and-error means of differentiating the various EDM pulses.

Therefore, there is a need to develop a highly stable EDM servo control system either to improve the current machining performance or to meet the future needs of machining advanced materials. König, et. al., [11]. Moreover, with the perpetual push towards unattended EDM operation, adaptive control system will continue to receive a definite amount of
research attention. Such a move will in turn create considerable economic benefits for EDM in terms of training and operating costs.

2.4.3 Improving the Performance Measures in EDM

It is noted that a vast majority of research work have been concerned with the improvement made to the performance indices, such as MRR, TWR and surface roughness. Much of this research has departed from the traditional sparking phenomenon yielding higher machining efficiency and better performance measures. This is partly due to the application of CNC to EDM facilitating the MRM and improving the tool wear compensation techniques. As a result, the potential of using simple tooling to generate complex 3D cavity without employing a costly 3D profile electrode was reported. Such a technique greatly benefits the EDM process by reducing the large proportion of cost and the time factor of producing the electrode, which accounts for over 50% of the total machining cost. Semon [147]. In addition, the surface quality of the EDMed part has been the main research focus generating a huge number of improvement methods varying from surface alloying and modification techniques to the addition of powder additives.

Hence, a constant drive towards appreciating the MRM, TWP and metallurgy of the EDMed surface will continue to grow with the intention of offering a more effective means of improving the performance measures. Furthermore, the traditional EDM will gradually evolve towards MEDM by
further manipulating the capability of CNC but the MRR will remain a prime concern in fulfilling the demand of machining part in a shorter lead time.

2.4.4 Developments in EDM Process

The different advances made at the EDM machine have jointly progressed with the growing applications of EDM process. EDM has long been employed in the automotive, aerospace, mould, tool and die making industries. It has also made a significant inroad in the medical, optical, dental and jewelry industries, and in automotive and aerospace R&D areas. Stovicek [148]. These applications demand stringent machining requirements, such as the machining of HSTR materials, which generate strong research interests and prompt EDM machine manufacturers to improve the machining characteristics.

In addition, the short product development cycles and growing cost pressures have forced the die and mould making industries to increase the EDM efficiency. Tzeng and Chen [102] One of the unique options of improving the machining performance involves the HMP combining EDM process with other material removal processes. The most popular and highly effective arrangement includes the USM delivering ultrasonic vibration to the electrode, which assists the sparking and flushing operations. However, Taylan, et. al., [149] noted that the current trend in tool and die manufacturing is towards replacing the EDM process with new machining techniques such as HSM. HSM process is just as capable as the
EDM process in machining hardened materials with 40–60 HRC. Therefore, HMP involving EDM will continue to draw intense research interests seeking innovative ways of improving the machining performance and expanding the EDM applications.

2.5 CONCLUDING REMARKS

The introduction of EDM to the metal cutting has been a viable machining option of producing highly complex parts, independent of the mechanical properties of workpiece material. This is by virtue of the capability of EDM to economically machine parts, which are difficult to be carried out by conventional material removal processes. With continuous improvement in the metal removal efficiency and the incorporation of numerical control, the viability of the EDM process in terms of the type of applications can be considerably extended.

The basis of controlling the EDM process mostly relies on empirical methods largely due to the stochastic nature of the sparking phenomenon involving both electrical and non-electrical process parameters. The complicated interrelationship between the different optimized process parameters is therefore a major factor contributing to the overall machining efficiency. However, several means of improving the machining performance commonly measured in terms of MRR, TWR and SR have been made with an overwhelming research interest being paid to the metallurgical properties of EDMed part. Thus, the EDM process needs to
be constantly revitalized to remain competitive in providing an essential and valuable role in the tool room manufacturing of part with difficult-to-machine materials and geometries.

2.6 LITERATURE REVIEW FOR PRESENT RESEARCH WORK

The tool taper angle, tool shape and size along with wear are of great importance because they adversely affect the accuracy of the machining features in sink-EDM process. The problem of tool wear is a well-known phenomenon in sink-EDM process. Mohri, et. al., [64]. This problem is easily overcome by using a number of tools to produce a cavity, but fabrication of complex-shaped tools is more expensive, time consuming and sometimes cost more than 70% of the total operation cost. Haas, Ozgedik and Cogun [150, 151]. Proposed to move a simple shaped tool along desired tool paths as a solution to these problems, Rajurkar and Yu [31]. A detailed study of EDM pocketing by Kruth, et. al., [152] focused on rotating cylindrical tool. Experiments were designed and conducted to investigate the MRR in EDM pocketing utilizing different tool diameters and machining areas with varied current levels. The EDM pocketing process was repeated using square tools that required higher flushing in order to achieve comparable MRR and in this case high tool wear was noted. Nonetheless, the use of square tools for eroding pockets comprising sharp corners and slots was suggested. Bayramoglu and Duffill [28] characterized
and analyzed the performance of cylindrical and 3D form tools used in the production of 3D complex shapes and cavities on a CNC EDM. They presented interesting experimental observation with detailed analytical results. However, the authors believe that the role of non-cylindrical tools (e.g. rectangular or square shaped tools), while machining in a layer-by-layer manner or suggestions of suitable techniques on the tool wear compensation should have been investigated. Yu, et. al., [35] used square shaped tools for 3-D micro EDM of cavities with sharp corners with tool path correction during the machining process to compensate for tool wear. Uniform wear was achieved on the tool by machining in a layer-by-layer manner along a programmed X-Y plane path. Square tools were deemed particularly useful for finishing parts containing sharp corners although precaution has to be taken to avoid deformation of the tool tip through discharges and path overlap. The use of square tools however, leads to less rotation and higher non-symmetrical tool wear. However, numbers of methods for tool wear compensation as suggested by Rajurkar, et. al., [153] depends highly on the value of the volumetric wear ratio.

Aforementioned literature review highlights the significance of tool wear on geometrical accuracy and MRR on the EDM process. For a specific machining situation, it appears that the operator can choose what sort of tool to use in terms of both shape and material make-up, but cannot detect how the tool wears or predict modification in both tool shapes and workpiece. Moreover, the full potential utilization of EDM process is not
achieved completely because of its complex and stochastic nature, with increased number of quantitative and qualitative parameters involved.

Traditionally, the selection of the most favorable process parameters was based on experience or handbook values, which produced inconsistent machining performance. However, the optimization of parameters now relies on process analysis to identify the effect of operating parameters on achieving the desired machining characteristics. The effect of process parameters has been investigated. Wang and Yan [154], Lin, et. al., [100, 101] studied the effect of current, polarity, voltage and spark on time on the EDM process by using Taguchi method. Tsai and Wang [96] compared the neural network models on MRR in EDM. Tsai and Wang [97] studied the effects of process parameters on surface finish in EDM. Lin and Ko [155] Employed grey relational analysis for solving the complicated interrelationships between EDM process parameters and the multiple performance characteristics.

Other works have applied the Taguchi approach to analyze and design the ideal EDM process. Marafona and Wykes [65] used the Taguchi method to improve the TWR by introducing high carbon content to the tool prior to the normal sparking process. Lin, et. al., [101] employed it with a set of fuzzy logic to optimize the process parameters considering the various performance measures. Tzeng and Chen [102] Optimized the high-speed EDM process by making use of the dynamic signal-to-noise (S/N)
ratio to classify the process variables into input signal, control and noise factors generating a dynamic range of output responses.

2.7 GAPS IN THE LITERATURE AND RESEARCH OBJECTIVES

A substantial amount of research has been carried out to identify the effect of various input parameters in sink-EDM process, so as to improve the process performance characteristics. On the other hand, literature review indicates that there is a distinct lack of systematic studies reported to identify the effect of tool taper angle and tool shape with size factor consideration as input process parameters in sink-EDM process using Design of Experiments (DOE) and Response Surface Methodology (RSM). Hence, for the present work, following specific objectives have been identified.

2.7.1 Research Objectives

1. To study the input-output relationships and the effect of input variables and their interactions on the responses.

2. To develop mathematical models by carrying out statistical regression analysis on the data set collected as per some specific design of experiments.
3. To investigate the effect of tool taper angle and tool shapes such as triangular, square, rectangular and circular with size factor consideration along with other parameters such as discharge current, pulse on-time, pulse off-time and tool area.

4. Analysis of the parametric influence along with the effect of tool taper angle and tool shapes with size factor consideration based on Response Surface Methodology (RSM).

5. Presenting the results in table and graphical form for easy analysis of the parametric influences along with the effect of tool taper angle and tool shapes with size factor consideration.

2.8 RESEARCH METHODOLOGY

The conventional statistical regression analysis based on Design of Experiments (DOE) provides a very good understanding of the effect of input variables on the responses of a physical system. Moreover, the input-output relationships developed in this method yield accurate results and the regression models can be used to predict the responses for a set of input variables.

In conventional statistical regression analysis of a system, only one response can be determined at a time, as the function of input process
parameters. However, in a multi-input and multi-output system, all the outputs are to be determined simultaneously and there might be some dependency among them. Thus, the above approach is used to predict the responses for a set of input process parameters.

Summary

An overview of the EDM process is given with a detailed literature review carried out on sink Electrical Discharge Machining (sink-EDM) process. The gaps in the literature for present research work have been identified. The objectives of the present research work are explained. The chapter ends with brief introduction to research methodology.