CHAPTER -1

INTRODUCTION
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1.1 HISTORY

Electrical Discharge Machining (EDM) is one of the most extensively used non-conventional material removal processes. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its added advantage in the manufacture of mould, die, automotive, aerospace and surgical components. In addition, EDM does not make direct contact between the electrode and the work piece, thus eliminates mechanical stresses, vibration problems and chatter during machining. The basis of EDM can be traced as far back as 1770, when English chemist Joseph Priestly discovered the erosive effect of electrical discharges or sparks [1]. However, it was only in 1943 at the Moscow University where Lazarenko and Lazarenko [2] exploited the destructive properties of electrical discharges for constructive use. They developed a controlled process of machining difficult-to-machine metals by vaporizing material from the surface of metal. The Lazarenko EDM system used resistance–capacitance type of power supply, which was widely used at the EDM machine in the 1950s and later served as the model for successive development in EDM [3]. It was only in the 1980s with the advent of Computer Numerical Control (CNC) in EDM that brought about tremendous advances in improving the efficiency of the machining operation. CNC has facilitated total EDM, which implied an automatic and unattended machining from inserting the electrodes in the tool changer to finished polished cavities [4]. These growing qualities of EDM have since then been intensely sought by the manufacturing industries yielding huge economic benefits and generating keen research interests.

1.2 EDM PROCESS

In EDM, material removal is achieved by erosion of the work piece as controlled discrete discharges are passed between the electrode and the work piece in dielectric medium as shown in Fig. 1.1. Important phases in electrical discharge machining are, pre-breakdown phase (a), breakdown phase (b), discharge phase (c), end of discharge phase (d) and post discharge phase (e) are shown in Fig. 1.2.
Antoine DESCOEUDRES [5] has given a simple explanation of the erosion process due to a single EDM discharge as depicted in Fig. 1.2. First, voltage is applied between the electrodes. As the potential difference increases between the two surfaces, the local dielectric fluid breaks down and ions are generated. Electric discharge occurs in area where the distance between the work and tool is minimum and electric field is strongest. Since, the two surfaces are completely immersed in
dielectric fluid even though the voltage has increased but the current is still zero. Electric field is strongest at the point where there is a least gap between the two electrodes. More and more ions start generating and thus decrease the insulating property of dielectric along a narrow gap between the two electrodes. Breakdown occurs at the closest points between the electrode and the work piece and discharge channel begins to form. At this point the current is still zero but the voltage reaches to its highest point. Then gradually current starts building and voltage decreases as shown in Fig. 1.2(b). The voltage continues to decrease while current continues to increase. This causes breakdown of dielectric and creation of plasma channel across the inter electrode gap [5,6].

Then the current and voltage both stabilizes and the situation is shown in Fig.1.2(c). Inside the plasma channel pressure and heat reaches to its peak value and material from the work piece gets melted. The molten material is held in place by the pressure of the vapor. Figure 1.2(d) show the condition when the voltage and current reaches to zero. Then there is sudden decrease in temperature and pressure of the discharge channel and it collapses. Molten metal is then expelled out from the surface of the work piece. Post-discharge phase is shown in Fig. 1.2(e), where the dielectric fluid rushes in, flushes the eroded particles and cools the surface of the electrode and the work piece. Recast layer is formed due to re-solidification of the un-expelled molten material back to the surface of the work piece. At this stage the electrical spark is completed and the condition is ready for the next spark.

The role of liquid dielectric is very crucial during EDM process. It cools the electrodes, builds up the high plasma pressure, enhances the flushing of the molten metal after the plasma collapses, solidifies the molten metal and flushes out the solidified particles. Post discharge stage is also important because cleaning of the spark gap occurs at this stage and machine is ready for the next discharge. If the particles remain the discharge gap, causes arcing and poor surface finish. For effective flushing of the particles dielectric is generally directed through the gap. In addition to this, electrode is given a pulsating movement which enhances the cleaning of the spark gap and brings fresh dielectric into the gap.

The surface finish and material removal rate depends on the electrode polarity, material of the electrode, duration of the discharge, discharge current and also on the dielectric cleanliness. High discharge current produce deep craters, high material removal rate and poor surface finish. Whereas, low discharge current will produce
small craters, better surface roughness but low material removal rate. In a rough
machining operation, high discharge current, long pulse duration and positive polarity
is preferred whereas in finish machining, short pulse-on time, low discharge current
and negative polarity of tool are used.

The material erosion mechanism primarily makes use of electrical energy and turns it
into thermal energy through a series of discrete electrical discharges occurring
between the electrode and work piece immersed in a dielectric fluid [7]. The thermal
energy generates a channel of plasma between the cathode and anode [8] at a
temperature in the range of 8000 °C to 12,000 °C [9] or as high as 20,000 °C [10]
initializing a substantial amount of heating and melting of material at the surface of
each pole. When the pulsating direct current supply occurring at the rate of
approximately 20,000–30,000 Hz [11] is turned off, the plasma channel breaks down.
This causes a sudden reduction in the temperature allowing the circulating dielectric
fluid to implure the plasma channel and flush the molten material from the pole
surfaces in the form of microscopic debris. This process of melting and evaporating
material from the work piece surface is in complete contrast to the conventional
machining processes, as chips are not mechanically produced. The volume of material
removed per discharge is typically in the range of $10^{-6}$–$10^{-4}$ mm$^3$ and the Material
Removal Rate (MRR) is usually between 2 and 400 mm$^3$/min [12] depending on
specific application. Since the shaped electrode defines the area in which the spark
erosion will occur, the accuracy of the part produced after EDM is fairly high. After
all, EDM is a reproductive shaping process in which the form of the electrode is
mirrored in the work piece [13].

1.3 PROCESS PARAMETERS

Some of the most important parameters implicated in the EDM manufacturing process
are the following ones:

i) *Discharge current:* It points out the different levels of power that can be
supplied by the generator of the EDM machine and represents the mean value
of the discharge current intensity.

ii) *Pulse-on time:* It is the duration of time (μs) the current is allowed to flow per
cycle. Material removal is directly proportional to the amount of energy
applied during this pulse-on time. This energy is controlled by the discharge
current and the duration of the pulse-on time.
iii) **Pulse-off time:** It is the duration of time (μs) between the two successive sparks (pulse-on time). This time allows the molten material to solidify and to be wash out of the arc gap. This parameter is to affect the speed and the stability of the cut. Thus, if the off-time is too short, it will cause sparks to be unstable.

iv) **Duty cycle:** It is a percentage of the pulse-on time relative to the total cycle time. This parameter is calculated by dividing the pulse-on time by the total cycle time (pulse-on time plus pulse-off time). The result is multiplied by 100 for the percentage of efficiency, called duty cycle.

v) **Dielectric pressure:** This is the flushing pressure of the dielectric jet which removes the chip or debris produced during the EDM process away from the gap zone. This value of pressure is measured by pressure gauge existing in the EDM machine.

vi) **Polarity:** The machine can run either in normal polarity or reverse polarity. The polarity normally used is straight (normal polarity) in which the tool is **negative** and work piece is **positive**, while in reverse polarity the tool is **positive** and work piece is **negative**.

### 1.4 MACHINING CHARACTERISTICS

The effectiveness of EDM process is evaluated in terms of its machining characteristics. The short product development cycles and growing cost pressures have forced the die and mould making industries to increase the EDM efficiency. The EDM efficiency is measured in terms of its machining characteristics viz. material removal rate, surface roughness and tool wear rate. The most important machining characteristics considered in the present work are:

i) **Surface Roughness** \((R_a)\): Surface finish is an essential requirement in determining the surface quality of a product. The average surface roughness is the integral absolute value of the height of the roughness profile over the evaluation length \((L)\) and was represented by the equation given below.

\[
R_a = \frac{1}{L} \int_{0}^{L} |y(x)| \, dx
\]  

(1.1)

Where ‘\(L\)’ is the length taken for observation and ‘\(Y\)’ is the ordinate of the profile curve.

ii) **Material removal rate** \((MRR)\): Material removal rate is a desirable characteristic and it should be as high as possible to give least machine cycle
time leading to increased productivity. Material removal is the difference of weight of work-piece before machining and after machining. It is calculated by the formula [1.2] as given below.

\[ MRR = \frac{W_i - W_f}{\rho \cdot t} \text{ mm}^3/\text{min} \]  

(1.2)

Where, \( W_i \) is the initial weight of work-piece in g; \( W_f \) is the final weight of work-piece after machining in g; \( t \) is the machining time in minutes and \( \rho \) is the density of work piece material.

iii) **Tool Wear Rate (TWR):** Tool wear rate is the difference of electrode weight before and after machining and is expressed as:

\[ TWR = \frac{E_i - E_f}{\rho_e \cdot t} \text{ mm}^3/\text{min} \]  

(1.3)

Where, \( E_i \) is the initial weight of electrode in g; \( E_f \) is the final weight of electrode after machining in g; \( t \) is the machining time in minutes and \( \rho_e \) is the density of electrode material.

1.5 TOOL MATERIAL

There is a vast range of materials used for manufacturing electrodes like electrolytic copper, graphite, brass, tungsten carbides, copper-tungsten alloys, silver-tungsten alloy, tellurium-copper alloys, copper-graphite alloys, etc. The most commonly used electrodes are: copper, brass, tungsten, zinc, and graphite. The most desirable properties of the electrodes are:

i) Easily machinable.

ii) Low wear rate.

iii) Good electrical and thermal conductivity.

iv) High melting temperature.

v) Resistance to deformation during machining.

vi) Cheap and readily available.

The above mentioned desirable properties provide general guidelines for electrode material selection.
1.6 APPLICATIONS
EDM can be employed to machine any material i.e. hard, tough, brittle, exotic etc. provided it has some minimum electrical conductivity. The manufactured of hardened steel dies is the field of application other than aerospace, automobile, tools and machine tool components. It is used for making through cavities and miniature holes. Application of EDM in die and mould engineering is exemplary. It is used in making dies for plastic injection moulding, pressure die casting, forging, stamping, coining, and forming. It is also used to make dies for extruding, wire drawing, press tools etc., which require through holes. It is used for tiny holes, orifices, and fragile features (micro sized slots). In case of making intricate shape dies the machining time has come down to 50% or less. EDMed dies are free of burrs and have higher life as compared to dies made by conventional methods. Matte finish obtained during EDM minimizes polishing time required. In EDM machining can be done even after heat treatment and can choose better die material which are extremely difficult to make otherwise, viz. squares, ‘D’ holes, splines, narrow slots and grooves, blended features etc.

In EDM, no mechanical forces act as in conventional machining; hence the process can be employed to machine thin and fragile components without any danger of damage due to such forces.

1.7 STATEMENT OF THE PROBLEM
The present work titled “Development of a hybrid model for optimal selection of electrical discharge machining process parameters for mould and die steel materials” has been undertaken keeping in consideration the following problems:

❖ EDM process heavily relies on operator’s experience and on conservative technical data provided by machine tool manufacturer, which often produces inconsistent machining performance.

❖ It has been recognized that process parameters such as discharge current, pulse-on time, pulse-off time, servo voltage and dielectric pressure should be selected to optimize the machining characteristics such as surface roughness, material removal rate and electrode wear rate. From literature review, it has been found that most influencing process parameters are discharge current,
pulse-on time and pulse-off time as their degree of contribution over machining characteristics are very significant.

❖ Surface roughness and material removal rate are identified as machining characteristics to be studied as they influence the productivity and quality of a product.

❖ Since, majority of the small scale industries uses die sinking EDM due to high cost of CNC EDM, therefore it was decided to obtain optimal process parameters for die sinking EDM so as to operate these machines as efficiently as possible.

❖ Die steel materials found wide applications in hot-work forging, extrusion, manufacturing punching tools, mandrels, mechanical press forging die, plastic mould and die-casting dies etc. The development of generic model for selection of optimal process parameters for these die steel materials was thus, very essential. Thus there is a need for development of a generic model for optimal selection of electrical discharge machining process parameters for mould and die steel materials.

❖ The developed generic model needs to be validated experimentally to ascertain its prediction accuracy.

1.8 OBJECTIVES OF THE PRESENT INVESTIGATION

The objectives of the proposed research study are briefly outlined as below:

➢ To identify and analyze the effect of most influencing process parameters and material properties, on machining characteristics like Material Removal Rate and Surface Roughness of die-sinking EDM process.

➢ To investigate the effect of theoretical and empirical models on machining characteristics.

➢ To investigate the working ranges and levels of the EDM process parameters using one factor at a time approach

➢ To determine the effects of selected process parameters on identified machining characteristics.

➢ To develop a hybrid model of the EDM process for a group of mould and die steel material for optimal selection of process parameters and prediction of surface roughness and material removal rate.
To validate the developed model and analyze the performance of developed model by performing experimentation for different combinations of electrode and work piece materials.

1.9 DIFFERENT PHASES OF EXPERIMENTATION

To accomplish the objectives, present work was divided in four phases.

Phase –I

Comprehensive literature review to:

- Identify and analyze the effect of most influencing process parameters on machining characteristics like Material Removal Rate and Surface Roughness of die-sinking EDM process.
- Investigate the effect of theoretical and empirical models on machining characteristics like surface roughness and material removal rate.

Phase –II

Finalizing the working range and levels of process parameters as discussed below:

- Developments of experimental set up for performing experimentation on die-sinking EDM and measuring the various machining characteristics.
- Investigation of the working ranges and the levels of the EDM process parameters (pilot experiments) affecting the selected machining characteristics, by using one factor at a time approach.

Phase –III

Developments of mathematical models of SR and MRR using RSM for five different moulds and die steel materials as per given methodology:

- Performing experimentation by using Central Composite Design (CCD) technique.
- Development of mathematical models and response surfaces of machining characteristics viz. surface roughness and material removal rate.
- Model adequacy tests for the developed models of SR and MRR.
- Conformity Experiments for the developed models.
- Investigating the effects of EDM process parameters on machining characteristics viz. surface roughness and material removal rate on AISI 1040, AISI 52100, AISI D2, AISI M2 and AISI P20 die steel material using copper and graphite electrode.
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Determination of optimal process parameters from the developed mathematical models using NSGA approach as given below:

- Development of single objective and multi-objective optimization models for SR and MRR using NSGA.
- Determination of Pareto-optimal sets in finish and rough machining region.
- Comparison of results of Experimental values and Pareto-optimal values in finish and rough machining region.

Phase –V

Development and validation of generic hybrid model:

- Development of a hybrid model for a group of mould and die steel materials using RSM-NSGA-ANFIS approach for prediction of SR and MRR.
- Validating and analyzing the performance of generic hybrid model with new work materials viz. AISI A2 and AISI D3 die steel material.

1.10 THESIS OUTLINE

The presentation of the research work in the form of thesis is organized in six chapters. The brief outline of the thesis is given as under:

Chapter one gives an introduction to the different topics in thesis. It deals with Electrical Discharge Machine Process, its working principle, process parameters, machining characteristics, tool materials, applications, statement of the problem, objectives of the present investigation and different phases of experimentation.

Chapter two contains current status of literature survey. Work done by various researchers have been classified into five major categories viz. machining theory based approach, experimental investigation, designed experiments, AI approach and hybrid model development approach. After a comprehensive study gaps in the literature have been identified and presented in the chapter.

Chapter three covers theoretical background of Response Surface Methodology approach adopted for experimentation; Genetic Algorithm optimization strategy used in single objective optimization and multi-objective optimization for selection of optimal process parameters and architecture of Adaptive Neuro-Fuzzy Inference System.
Chapter four describes the experimental set up for conducting the experiments, process parameters and machining characteristics considered in the present work. It also includes pilot experiments to know the variation of process parameters on machining characteristics and to ascertain the range of process parameters for model development.

Chapter five deals with the development of generic hybrid (integration of RSM-NSGA II- ANFIS) model, for a group of mould and die steel materials and its validation. It deals with the development of mathematical models from the experimental data and its statistical significance. Conformity experiments for validating the developed models are also presented in this chapter. Single objective and multi-objective optimization of machining characteristics are also discussed. Finally, design, development and validation of ANFIS models are described in this chapter.

Chapter six discusses the conclusions and limitations of the present work. Scope for future work is also outlined in the last.

The literature referred for this entire work is listed in numerical order at the end of the thesis according to their order of appearance in the text. The appendices mentioned during the chapters are also attached. The lists of publications based on the present research work are given in Appendix-J.