## INTRODUCTION

Electrical discharge machining (EDM) is one of the earliest non-traditional machining processes. It is an electro-thermal machining process where electrical energy is used to generate electrical spark and material removal mainly occurs due to thermal energy of the spark. Electrical discharge machining mainly consists of two major components that are machine tool and a power supply. The machine tool holds a shaped electrode, which advances into the workpiece and produces a shaped cavity. The electrical spark is produced from a power supply. It produces a high frequency series of electrical discharges between the electrode and the workpiece, which remove metal from the workpiece by thermal erosion or vaporization [1-2]. Fig. 1 is showing the electric setup of the electric discharge machining process. The tool is made cathode and work piece is anode and a potential difference is applied between the tool and work piece which finally leads to generation of spark. An important characteristic of EDM is that both the tool and work piece must be electrically conductive and completely immersed in a dielectric medium [3] supplied continuously by the pump as show in the Fig. 1.

Depending upon the applied potential difference and the gap between the tool and workpiece, an electric field would be established [4]. As the electric field is established between the tool and the job, the free electrons on the tool are subjected to electrostatic forces. As a result of which electrons are plucked out from the tool and then accelerated towards the job through the dielectric medium. As they gain velocity and energy, and start moving towards the job, there would be collisions between the electrons and dielectric molecules. Such collision may result in ionisation of the dielectric molecules. Thus, as the electrons get accelerated, more positive ions and electrons would get generated due to collisions. This cyclic process would increase the concentration of electrons and ions in the dielectric medium between the tool and the job at the spark gap creating a channel known as “plasma”. The electrical resistance of such plasma channel would be very less. Thus all of a sudden, a large number of electrons will flow from the tool to the job and ions from the tool to the job. This is called avalanche motion of electrons. Such movement of electrons and ions can be visually seen as a spark. Thus the electrical energy is dissipated as the thermal energy of the spark. The high speed electrons then impinge on the job and ions on the tool. The kinetic energy of the electrons and ions impact with the surface of the job and tool respectively would be converted into thermal energy or heat flux. Such intense localised heat flux leads to extreme instantaneous confined rise in temperature which would be in excess of 10,000°C. Such localised extreme rise in temperature leads to material removal. The molten metal is not removed completely but only partially. An important advantage is that in EDM process there is no direct contact between the electrode and the work piece where it can eliminate mechanical stresses, chatter and vibration problems during machining. This promotes Electric discharge machining (EDM) to machine difficult-to-machine materials and high strength temperature resistant alloys too. It is mainly used by toolmakers for complex injection moulds, punch dies and cavities made from hard to machine materials. Generally kerosene or deionised water is used as the dielectric medium. A proper gap must be maintained between the tool and the workpiece in order to generate the spark. Various types of products can be produced and/or finished using EDM such as dies, moulds, parts of aerospace, automotive industry and surgical components etc. This paper presents the various research issues in EDM along with the modelling technique in predicting EDM performances.

### Keywords
- Electrical discharge machining (EDM), electrode, spark, workpiece, gap, conductivity.

### Abstract
Electrical discharge machining (EDM) is one of the earliest non-traditional machining processes. EDM process is based on thermoelectric energy between the work piece and an electrode. A spark occurs in a small gap between the work piece and the electrode and removes the material from the work piece through melting and vapourising. The electrode and the work piece must be electrically conductive in order to generate the spark. Various types of products can be produced and/or finished using EDM such as dies, moulds, parts of aerospace, automotive industry and surgical components etc. This paper presents the various research issues in EDM along with the modelling technique in predicting EDM performances.

### Figure 1: Electrical setup for EDM process.
materials in small batches or even on job-shop basis [5]. When the potential difference is withdrawn, the plasma channel is no longer sustained. As the plasma channel collapses, it generates pressure or shock waves, which evacuates the molten material forming a crater of removed material around the site of the spark.

**Material removal mechanism**

The system is connected in forward biasing where the positive terminal of power supply is connected to workpiece and the negative terminal is applied to the tool or electrode. Fig. 2 illustrate the mechanism, when a potential difference is applied an electric field is established between the tool and workpiece which will pluck the free electrons from the tool in large number and they are accelerated towards the workpiece because of large electrostatic force of field. Thus there will be collision of electron with dielectric molecules. As the electrons are highly energetic they will ionise the dielectric molecule. After the primary collision the electrons are again accelerated which leads to the more and more collision and creates a plasma channel between tool and workpiece. The resistivity of the channel will be very less and electrons suddenly move to the workpiece with high energy. Now workpiece will be continuously impinged by electrons and on impingement the associated kinetic energy gets converted to thermal energy causing localised melting leading to material removal in form of debris which is continuously being flush off by the dielectric.

**Important parameters of EDM**

The important parameters of Electrical discharge machining process are as listed below:

a. Spark On-time (pulse on time or Ton): The duration of time the current is allowed to flow per cycle. Material removal is directly proportional to the amount of energy applied during this on-time. This energy is really controlled by the peak current and the length of the on-time.

b. Spark Off-time (pulse off time or Toff): The duration of time between the sparks occurrence. This time allows the molten metal 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.

c. Arc gap (or gap): The Arc gap is distance between the electrode and workpiece during the process of EDM. It may be called as spark gap. Spark gap can be maintained by servo system.

d. Discharge current (Ip): Current in ampere allowed to per cycle. Discharge current is directly proportional to the Material removal rate.

e. Duty cycle (τ): It is a percentage of the on-time relative to the total cycle time. This parameter is calculated by dividing the on-time by the total cycle time.

f. Voltage (V): It is a potential that can be measure by volt it is also effect to the material removal rate and allowed to per cycle.

g. Diameter of electrode (D): It is the electrode diameter used in EDM process.

h. Over cut – It is a clearance per side between the electrode and the workpiece after the machining operation.

**Characteristics of EDM**

EDM specification by mechanism of process, metal removal rate and other function is shown in Table1.

| Table 1 Specification on EDM |
|-----------------------------|
| Mechanism of process | Controlled erosion (melting and evaporation) through a series of electric spark |
| Spark gap (mm) | 0.10 – 0.500 |
| Spark frequency (kHz) | 200 – 500 |
| Peak voltage across the gap (V) | 30 – 250 |
| Metal removal rate (mm³/min) | 5000 |
| Specific power consumption (W/mm³/min) | 2-10 |
| Dielectric fluid | EDM oil, Kerosene liquid paraffin, silicon oil, deionized water etc. |
| Tool material | Copper, Brass, graphite, Ag-W alloys, Cu-W alloys |
| MRR/TWR | 0.1-10 |
| Materials that can be machined | All conducting metals and alloys. |
| Shapes | Micro holes, narrow slots, blind cavities. |
| Limitations | High specific energy consumption, non-conducting materials can’t be machined. |

**Important performance measures of EDM**

There are several different types of machines and industrial applications that use the EDM process for high precision machining of metals with Die Sinking and Wire EDM being the two major EDM variants. The most common performance measures for EDM are:

a. Material removal rate (MRR), measured in mm³/min.

b. Tool wear ratio (TWR), measured as tool removal rate to workpiece removal rate and surface quality (SQ) of the eroded cavity, measured in µm, Ra.

In addition, the surfaces finish, dimensional accuracy and geometry of the electrode, as well as the material properties, such as thermal conductivity, and wear resistance affect EDM performance measures too. Generally, depending on the MRR, EDM can be characterized as: roughing, semi-roughing, and finishing. EDM techniques have developed in many areas. Trends on activities carried out by researchers depend on the interest of the researchers and the availability of the technology. In a book published in 1994, Rajurkar [6] has indicated some future trends activities in EDM: machining advanced materials, mirror surface finish using powder additives, ultrasonic-assisted EDM and control and automation.
Areas of Research

 EDM is a non-traditional concept of machining which has been widely used to produce mould and dies in industries. It is really a very vast field and comprises of various areas of research. The different issues that can be considered for research in EDM can be Materials, Optimization of process parameters, variants of EDM, Automation, Green manufacturing and electrode manufacturing. These issues are explained in detail as under:

Materials

 EDM was previously used for the machining of hard and brittle materials like steel, titanium, tungsten carbide etc. It is mainly employed for semi-roughing and finishing operation apart from some application where it is also used for roughing operation. With the development, the demand for advance materials as super-alloys (such as Nickel based super alloys GH4169 used in aeronautical applications and turbine component, Ti-6Al-4V alloys also used in aeronautical applications), Composites (such as aluminium based metal matrix composites having potential for advanced structural applications due to high specific strength as well as good elevated temperature resistance, carbon fibre reinforced carbon composites used in the aeronautic and aerospace industry including rocket exit nozzles, nose caps, pistons for internal combustion engines etc.) and ceramics (such as aluminium matrix reinforced with ceramic particles in the form of grains, fibre used in the automotive industry) increases. They have attractive properties i.e., high strength, high bending stiffness, good damping capacity, low thermal expansion, better fatigue characteristics. More and more investigations are focused on machining of these materials with EDM as they show better material removal rate and surface finish at increased current which was not obtained with other non-traditional processes. Lok et al. [7] investigated the processing of two advanced materials Sialon and Al2O3-TiC by using wire EDM (WEDM). MRR and surface finish was taken as output parameters. The surface damage was evaluated by flexural strength data. The variability of flexural strength data was also analyzed by weibull stastical method. They conclude that mean flexural strength changes from 32% to 67% due to thermal spalling erosion mechanism of wire-cut EDM process. Yan et al. [8] machined aluminium matrix composites (Al2O3p/6061 Al) using WEDM. The effect of pulse on time, cutting speed, width of slit, surface roughness was studied. It was observed that that the cutting speed, surface roughness and width of the slit significantly depend upon volume fraction of Al2O3 particles. Less volume percentage of reinforcement increases the surface finish, improves width of slit. Hascaley et al. [9] performed an experiment for finding out the machining characteristics of AISI D5 tool steel in WEDM. The author concluded that intensity of process energy affect the surface roughness as well as micro cracking. The wire speed and fluid pressure do not have much influence.

Optimization/Selection of Process Parameters

 The various performance measures of EDM process are Material removal rate (MRR), surface quality (SQ) and tool wear ratio (TWR). These performance measures are directly linked with the various parameters of the process which includes spark on and off time, flushing pressure, current etc as they only contributes in the process performance. So the better optimization of process parameters would yields in better performance of EDM process. So more and more researchers are focusing in the optimization of process parameters either by closely examining the experimental procedure or by carrying out the simulation of EDM process. Marafoa et.al [10] used fractional factorial method developed by Taguchi for optimizing material removal rate using EDM with copper–tungsten electrodes. They suggested a new methodology using the black layer for improving EDM performance. They said that the percentage of carbon in the ‘black’ layer is very important in the improvement of the EDM performance. Shabgard et al. [11] applied fuzzy approach to select machining parameters in electrical discharge machining (EDM) and ultrasonic-assisted EDM processes. The fuzzy models were developed based on the electrical machining of tungsten carbide. They concluded that in machining of tungsten carbide the material removal rate and surface roughness increased with an increase in pulse duration and discharge current. Also it was noticed that tool wear ratio decreased with an increase in pulse duration and discharge current. Comparison and validation of fuzzy results with experiment findings verified the high accuracy of models. Lin et al. [12] used grey-fuzzy logic based on orthogonal array for optimizing the electrical discharge machining process with multiple process response (electrode wear ratio, material removal rate and surface roughness). They concluded that these approaches can greatly improve the process responses in the electrical discharge machining process.

Variants of EDM

 Die sinking EDM, Wire electrical discharge machining (WEDM), Micro- EDM, Dry EDM, Rotary disk electrode electrical discharge machining (RDE-EDM) are some of the variant methods of EDM. Die sinking process can machine complex three-dimensional cavities. Wire-cut EDM (WEDM) and Rotary Disk electrical discharge machining process (RDE-EDM) has the ability to machine conductive and high strength and temperature resistive (HSTR) materials with the scope of generating intricate shapes and profiles. Micro-EDM is helpful for conventional precision engineering purposes as well as for machining of micro holes molds, inserts etc. Dry EDM uses gas as dielectric fluid, and high MRR can be obtained to cut high strength engineering materials with the presence of oxygen. Die sinking, rotary disk electrode EDM and WEDM showed great potential in machining of advanced materials, Dry EDM can maintain the ecological and economic balance and micro EDM can provide precision machining of micro holes. Gokler et al. [13] performed experiments to optimize the cutting and offset parameter combination for WEDM process to achieve the desired surface roughness. They has performed experiments on 1040 steel material of thickness 30, 60 and 80 mm and on 2379 and 2378 steel materials of thickness 30 and 60 mm. It was concluded that increase in the work piece thickness creates better surface roughness characteristic. Yan et al. [14] investigated effects of various machining parameters on the quality of the micro-hole machining of carbide by EDM. Fuel injector valves, parts and components for medical devices, fibre optic connectors, micromachining, stamping tools and micro electronics parts are the examples of miniaturized and smaller size parts produced by the micro-EDM technology. V.Raman et al. [15] reported that helium and argon can be used as a dielectric medium to drill holes using copper electrodes. Later on Kunieda et al. [16] confirm that by introducing oxygen gas into the discharge gap increases the material removal rate in water as a dielectric medium. Soni and Chakrvaverti [17] introduced rotary disc for grooving operation on titanium alloy.

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The rotary electrode was placed above the work material. The difficulty of debris problem was encountered the research work i.e. lower metal removal rate and arching occurs due to the accumulation of debris particle between the electrode and work piece.

**AUTOMATION**

A great attention is being focused in the implementation of intelligent CAD/CAM tool for reducing the tooling problem and manual intervention in the EDM machining. For machining of any complicated profile the tool movement path is generated by the CAD system for example as in case of CNC machining. The complicated profile region is divided into sub-regions and accordingly the path for the movement of electrode is generated. The aim is to develop a user friendly CAD tool that supports EDM machining rapidly and economically with ease. Kong et al. [18] proposed an automated method for patching parting surfaces that have holes or non-cylindrical hollow features. Alok et al. [19] developed a method that locates the part lines and creates the parting surface of multi-piece moulds and can cope with the production of complex parts.

**GREEN MANUFACTURING**

Modern industries are focusing much on the possibilities for moving towards “green manufacturing” so that their harmful impacts on the environment can be minimized to maximum possible extent. In any variants of EDM the dielectric fluid turns into waste after certain cycles, is found not only affecting the environmental balance as after use it mixes with soil and affects its fertility but also affect the economic impact because of use of dielectrics for only short run. This is being used as an indicator for EDM’S manufacturer to seek for more environmental friendly dielectric. Hence more and more researches are focused on EDM with deionized water and dry EDM as they don’t have any problem with their disposal. The deionized water found a great potential to be use as a dielectric, also it is cheap and non polluting. A research conducted by Kwan Chung Do et al. [20] showed that surface finish of micro-edm hole using deionized water is greatly improved. Dry EDM uses gas as dielectric fluid, and high MRR can be obtained to cut high strength engineering materials with the presence of oxygen [21].

**ELECTRODE MATERIALS**

Traditional electrodes used in EDM include Brass, Copper, tungsten, Zinc and graphite. Most of these electrodes experience problems as severe wear, brittleness, low mechanical strength and etc. Thus for obtaining desired machining performance researches are going on for developing electrode materials based on the concept that the properties of the electrodes such as melting point and electrical conductivity etc. Zhang et al. [22] suggested that Cu-graphite, Cu-ZrB2 and Cu-TiB2 composites has good capabilities of removing material with little wear loss. Tsai et al. [23] studied the EDM performance of Cr/Cu-based composite electrodes. Their work reveals that the Cr/Cu-based composite electrodes obtained a higher MRR than Cu metal electrodes and fewer cracks were present on the machined surface. Furthermore, the chromium (Cr) elements in the composite electrode migrated to the work piece, resulting in good corrosion resistance of the machined surface after EDM.

**RAPID ELECTRODE MANUFACTURING**

Electrode is an important organ of EDM process because the shape of the electrode is finally transferred to the work piece for achieving the desired profile. If any complicated profile is encountered then electrode manufacturing accordingly becomes difficult to produce. Also in mould and die production EDM cycle can account for 25 to 40% of the lead time, out of which the electrode production represents over 50% of the cost and time of an EDM operation. Thus a systematic system needs to be developed that can accelerate the electrode manufacturing time whether it is any shape of electrode so that the time and cost involved in electrode preparation can be minimized and economic balance can be established. Thus a great attention is focused in the concerned respect by integrating it with many computer assisted processes e.g. Rapid prototyping (RP), Finite element method (FEM). Allan et al. [24] investigated on electroforming of rapid prototyping mandrels for electro-discharge machining. A conclusion was drawn that thin walled copper electroforms backed up with suitable filler materials are ideal for use as electro-discharge machining electrodes. Hsu et al. [25] worked on EDM electrode manufacturing using RP combining electroless plating with electroforming. They concluded that test results indicate that no crack was found on the electrode and that the electrical discharge machining effects are promising.

**MODELLING TECHNIQUES**

EDM process is subjective by many factors. Different techniques viz. dimensional analysis, mathematical and thermal modelling, soft computing approach and etc. are employed to envisage the output of the process mainly the surface finish, tool wear and material removal rate (MRR). The different techniques and investigations related to them are given in Table 2.
The vibrational behaviour of the electrode wear study on the EDM of silicon carbide was investigated by Bojorquez et al. [19].

Pandit and Rajurkar [43] illustrated the potential prospects of EDM using ANN. The electric discharge machining of hardened tool steel using Taguchi method was conducted by Jousa et al. [26].

Tantra et al. [35] tested the validity of the model proposed by Heuvelman for erosion strength of material to predict tool wear. Patel et al. [31] developed the anode erosion model which accepts power as boundary condition at anode interface and assumed to produce a Gaussian-distributed heat flux on the surface of anode material.

A model on variable mass and cylindrical plasma was introduced by Eubank et al. [32].

McGeough and Rasmussen [33] proposed a model for electro discharge texturing based on the effect of dielectric fluid and in particular the influence of change in the resistance in the dielectric during each voltage pulse.

Perez et al. [34] presented a model for relative power dissipation by taking into account the different current emission mechanism and cathode space-charge characteristics valid for refractory and non-refractory materials.

Other methods

Pandit and Rajurkar [43] illustrates the capability of EDM to economically machine parts, which are highly complex parts, independent of the mechanical properties of work piece 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 capacity of machining hard and difficult to machine parts has made EDM as one of the most important machining processes. Absence of mechanical stresses due to nonexistence of direct contact between tool and work piece makes it more promising machining operation especially for brittle structures. More and more application of EDM in all around propels to discover all the related specifics which can only be fulfilled by discovering the various areas of interest in EDM. An attempt is made to list some important areas of interest in EDM. The different other aspects continuing from here could become a prominent future aspect for researchers.

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