1.1 MACHINING OF ADVANCED ENGINEERING MATERIALS

Stiff market competition, scientific and engineering advances along with continuously growing demand for improved product performance has led to the development of an ever growing variety and quality of materials such as carbides, ceramics, composites, semiconductors, variety of glass, diamond, etc. These advanced exotic engineering materials have wide range of applications in various fields of engineering such as die and molded parts, automobile, electronics, avionics, communication and medicine. These newly developed materials have high strength and stiffness at elevated temperatures, extreme hardness, high brittleness, high strength to weight ratio, high corrosion and oxidation resistance, and chemical inertness. Although such properties result in superior product performance; nevertheless, it is difficult to machine these materials by conventional methods. This situation has given a new impetus to the development of non-traditional machining processes since early 1940s, where in material is removed by mechanical means (USM, AJM, WJM), thermal erosion (EDM, LBM, EBM), anodic dissolution (ECM), chemical reaction or combination of two or more than two processes called hybrid machining (EDAG, ECSM). Jain N.K and Jain V.K [1]; Benedict GF [2]; McGeough JA [3]; Merchant ME [4], Kalpakjian S and Schmid SR [5].
1.2 NON-TRADITIONAL MACHINING PROCESSES

The following processes fall under the category of non-traditional machining:

- Ultrasonic Machining (USM)
- Abrasive Water Jet Machining (AWJM)
- Water Jet Machining (WJM)
- Chemical Machining (CM)
- Electrochemical Machining (ECM)
- Electrical Discharge Machining (EDM)
- Electrochemical Grinding (ECG)
- Electron-Beam Machining (EBM)
- Laser-Beam Machining (LBM)
- Plasma Machining (PM)
- Hybrid Machining (EDAG, ECSM)

These processes find their application when traditional machining processes are not suitable, satisfactory, economical, or even impossible, for the following reasons:

- The hardness and strength of the material is very high (typically above 400 HB) or the material is too brittle.
• The work piece is too flexible, slender, or delicate to withstand the cutting or grinding forces, or the parts are difficult to hold in a fixture – that is, to clamp in work holding devices.

• The shape of the part is complex, including such features as internal and external profiles or small-diameter holes of fuel-injection nozzles.

• Surface finish and dimensional tolerance requirements are more rigorous than those obtained by other processes.

• Temperature rise and residual stresses in the work piece are not desirable or acceptable.

1.3 ELECTRICAL DISCHARGE MACHINING PROCESS

1.3.1 History

Electrical Discharge Machining (EDM) process is a well known modern machining technique with a distinct advantage, as a result of which its use is becoming more and more decisive. The basis of EDM can be traced as far back as 1770, when English chemist Joseph Priestley discovered the erosive effect of electrical discharges or sparks. Webzell S [6]. Joseph Priestley also investigated (1776) (Fig. 1.1 (b)) the influence of the electrode material and of the discharge current on the crater size. He also examined the spots with a microscope, both the shining dots that formed the central spot, and those which formed the external circle, appeared evidently to consist of cavities. However, EDM process has evolved only
since its discovery in 1943 at the Moscow University where Russian scientist B.R Lazarenko and N.I. Lazarenko [7] exploited the destructive properties of electrical discharges for constructive use in a simple sink-EDM application. 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. A.L. Livshits [8].

![Diagram](https://example.com/diagram.png)

**Fig. 1.1 (a)** Engraved plate sent by Alessandro Volta to Joseph Priestley, showing the spark produced by short-circuit of a Leyden jar (1775)  
**Fig. 1.1 (b)** Sketches of erosion craters on cathode surface, observed by Joseph Priestley (1776)

There have been similar claims made at about the same time when three American employees came up with the notion of using electrical charges to remove broken taps and drills from hydraulic valves. Their work became the basis for the vacuum tube EDM machine and an electronic-circuit servo system that automatically provided the proper electrode-to-workpiece spacing (spark gap) for sparking, without the electrode
contacting the workpiece. E.C. Jameson [9]. 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 a finished polished cavity or cavities. L. Houman [10]. These growing merits of EDM have since then been intensely sought by the manufacturing industries yielding enormous economic benefits and generating keen research interests.

1.3.2 Introduction to EDM Process

It is very difficult to describe Electrical Discharge Machining (EDM) process because of its complex and stochastic nature. Most parts are invisible accompanied by some physical and chemical phenomenon. Sound, heat, light and electromagnetic radiations until today, they are neither completely understood, nor even not computable. State of art EDM technology always aims at improving output parameters. Speed, accuracy and surface finish is more important in EDM process and have been achieved mostly with improvements in robotics, atomization, process control, dielectric, flushing methods and generator design. EDM is a process where cutting material and material being cut do not touch each other, there is always a physical gap between the two. Probably this is the gap which has created perceptual gap in understanding EDM process too. However, nowadays it is the most widely used advanced machining process.
The Electrical Discharge Machining (EDM) works on the principle of erosion of metals by spark discharges. The EDM is one of the most accurate manufacturing processes available for creating simple or complex shapes and the geometries within parts and assemblies of extremely hard materials (fragile) that are difficult to machine using conventional methods, as it works using electrical energy turned to thermal energy rather than cutting. In EDM the chips are not mechanically produced unlike the conventional machining, 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 – 400 mm$^3$/min depending on specific application. Kalpajian S and Schmid SR [5]. Consecutively thousands of sparks per second are generated and each spark produces a tiny crater, in the material along the cutting path by melting and vaporization, thus eroding the workpiece to the shape of the tool. Konig, et. al., [11]. The dielectric (non-conducting) fluid flushes out the chips and confines the spark Tsai, et al., [12]. Each spark produces a temperature between 8,000 – 12,000 °C. G. Boothroyd and Winston [13] or as high as 20,000 °C. J.A. McGeough [14]. The size of micro crater depends on energy turned out by the spark generator pulsating direct current at 20,000 – 30,000 Hz. Krar and Check [15]

1.3.3 Types of EDM Processes

Traditionally, EDM has been classified into two distinct categories 1) Sink-EDM (ram or probe) process 2) Wire-cut EDM process, because of the
different ways adopted in performing the process. In sink-EDM process a copper/graphite electrode having the reversed shape of the part to be machined is fed into the workpiece from the end of the vertical ram. This type of EDM is usually performed in an oil based dielectric fluids. Sink-EDM process can cut a hole into the part without having a hole pre-drilled for the electrode. The cutting pattern is usually CNC controlled. In many EDM machines electrodes can be rotated about two – three axis allowing for cutting of internal cavities.

Wire-cut EDM is used primarily for shapes cut through a selected part or assembly. With a wire-cut EDM machine if a cut out need to be created, an initial hole must first be drilled in the material, and then the wire can be fed through the hole to complete machining. Usually in wire-cut EDM, a thin single strand copper/brass wire is fed through the workpiece. The wire, which is constantly fed from spool, is held between upper and lower guides. The guides move in the X-Y plane, and some times the upper guide can also move independently giving rise to transitioning shapes (Circle at the bottom and square at the top). This gives a wire-cut EDM the ability to be performed to cut very intricate and delicate shapes. Figure 1.2(a) illustrates the sink-EDM process and Fig. 1.2(b) illustrates Wire-cut EDM process.
Fig. 1.2 Schematic diagrams of (a) Sink-EDM (b) Wire-cut EDM processes
1.4 BASIC PRINCIPLES OF EDM PROCESS

1.4.1 Theories of Material Removal in EDM Process

The removal of material in Electrical Discharge Machining (EDM) process is based upon the erosion effect of electric sparks occurring between two electrodes. Several theories have been put forth in attempts to explain the complex phenomenon of "erosive spark". The following are the theories:

1. Electro-Mechanical Theory
2. Thermo-Mechanical Theory
3. Thermo-Electric Theory

1.4.1.1 Electro-Mechanical Theory

This theory suggests that abrasion of material particles takes place as a result of the concentrated electric field. The theory proposes that the electric field separates the material particles of the workpiece as it exceeds the forces of cohesion in the lattice of the material. This theory neglects any thermal effects. Experimental evidence lacks supports for this theory.

1.4.1.2 Thermo-Mechanical Theory

This theory suggests that material removal in EDM operations is attributed to the melting of material caused by "flame jets". These so-called flame jets are formed as a result of various electrical effects of the discharge.
However, this theory does not agree with experimental data and fails to give a reasonable explanation of the effect of spark erosion.

1.4.1.3 Thermo-Electric Theory

This theory, best-supported by experimental evidence, suggests that metal removal in EDM operations takes place as a result of the generation of extremely high temperature generated by the high intensity of the discharge current. Although well supported, this theory cannot be considered as definite and complete because of difficulties in interpretation.

While several theories, how EDM process works have been advanced over the years, most of the evidence available supports the thermoelectric model. The following description explains the theory behind the generation of spark erosion in the EDM process. As explained earlier in the article (1.3.2), EDM process uses electric energy by discharge which occurs as a result of dielectric breakdown between negative tool electrode and positive workpiece. As tool electrode approaches the workpiece, the electric field between tool electrode and workpiece becomes larger and larger, and then it comes to a point where a spark occurs. This is known as the fluid-ionization point and it is based on the dielectric strength of the fluid and the gap between the electrode and workpiece. Dielectric fluid has non-conductive property which is between anode and cathode. In general, when the machining starts at 200V as the input voltage, with normal gap between two electrodes the breakage of insulation occurs is usually 40 μm. When
discharge occurs, the voltage drops about to the range of from 25V to 45V. On the other hand, the amplitude of discharge current increase to a constant value predetermined.

Four types of gap conditions, open, spark, arc, and short, exist in the EDM process, as shown in Fig. 1.3. Qu, et. al., [16] it can be seen that sparks or effective discharge requires some delay time before the discharge current reaches its nominal value. The arcs, however, require negligible or zero delay time and occur at a lower breakdown voltage due to partially de-ionized dielectric. When the distance between the two electrodes is far enough, an open voltage pulse occurs with no current. A short circuit pulse is the result of direct contact between the electrode and the workpiece.

The debris/waste particles in the gap may form a bridge between two electrodes to create a short circuit. Flushing with the high pressure de-ionized dielectric is the way to prevent it. Sparks are the desired gap condition in EDM. Arcs, which damage the surface finish and dimensional accuracy, should be avoided. In order to optimize the EDM process, different types of monitoring and control systems have been developed, such as the ignition delay monitoring system. Beste, et. al., [17], Diode discharge monitoring system (DDS) and Radio Frequency (R.F) monitoring system. Pugsley, et. al., [18] and EDM discharge parameter monitoring system. Guilemany, et. al., and Hung, et. al., [19, 20]
1.4.2 Evolution of a Single Spark in the EDM Process

The four illustrations in Figure 1.4 are to show what is believed to happen during the generation of a single spark in the Electrical discharge machining (EDM) process. Explanations, however, exist that are accepted by most researchers. According to this theory Tlusty, Stevens, et. al., [21, 22], an electrical discharge between the tool electrode and the workpiece proceeds in four successive steps:

![Diagram of EDM process: Current and Voltage over time with labels: Open, Spark, Arc, Short]
1. The Ignition Phase

2. Formation of the Plasma Channel

3. Melting and Evaporation of Workpiece Material

4. Ejection of the Liquid Molten Material

1.4.2.1 The Ignition Phase

An electrical tension is applied between electrode and workpiece, creating an electrical field, characterized by the voltage gradient, expressed by the ratio of tension to distance, as well as some other items (roughness profile of tool, workpiece and debris in the gap, etc.). At the places where the gradient is maximal (usually at the highest points on the surface), electrons are emitted by the cathode (Fig. 1.4(a)). These electrons are called the primary electrons. The primary electrons are attracted by the anode and start moving towards it. On their way through the dielectric, the primary electrons collide with metal atoms of the dielectric. As a consequence, these dielectric atoms split up in to positive ions and electrons. These are called the secondary electrons (Fig. 1.4(b)).

1.4.2.2 Formation of the Plasma Channel

The positive ions originating from the dielectric are attracted towards the cathode. When they hit the cathode, they free some more electrons. This process is called the secondary emission. These electrons also move towards the anode and split up some more neutral dielectric atoms. The
current, created by both the electrons and the ions increases drastically and the dielectric starts heating locally. This decreases the electrical resistance and the current increases further. This phenomenon occurs like a kind of avalanche. The dielectric in the gap turns into vapor due to continuous heating and even plasma channel is created (Fig. 1.4(b)). The plasma channel is characterized by high pressure and temperature.

The formation of the plasma channel is also called the voltage breakdown because when the plasma channel is created, the voltage drops from higher value, to a user specified open circuit tension to the breakdown voltage which is determined by the material combination of electrode and workpiece (for the copper-steel combination it is from 20 to 25V). In normal cases, the voltage breakdown is initiated when the value of the electrical field reaches about $10^4$ V/mm. The time which elapses between applied voltage and the breakdown voltage (and thus also the beginning of the discharge) is called the ignition delay time.

This description is valid for clean dielectric. During machining, however, debris particles (the chips) caused by machining and other particles caused by the decomposition of the dielectric due to the high temperatures, are present in the dielectric fluid. Furthermore, powder particles can be added on purpose to the dielectric. In these cases, the particles in the dielectric form discharge paths which increase the voltage gradient. Consequently, the discharge takes place more easily and the spark gap is increased.
Fig. 1.4 Generation of a single spark in the EDM process
1.4.2.3 Melting and Evaporation of Workpiece Material

The plasma channel is maintained by the EDM machine for a user specified time. During this time, the anode and cathode surfaces are bombarded by electrons and ions respectively. When an electron or an ion collides with the surface, its kinetic energy is transformed into heat (Fig. 1.4(c)). This heat induces melting and a partial evaporation of the surface. The amount of molten material depends among other things from the number of electrons or ions that collide with the surface. The number of colliding particles per discharge depends on the current of the discharge and the discharge time.

There is an important difference in mass between electrons and ions. Metal ions are much heavier than electrons and so their kinetic energy is much higher (at least when they have the same speed as an electron). However, due to the higher inertia of ions, it takes more time to bring them to a certain speed. Therefore, when short discharge times are applied (less than 1ms) especially the electrons cause a high heat while only a limited amount of ions collide with the cathode. The speed of the ions is still low, so they need time to travel over a certain distance. It is only when longer discharge times are used that many ions can reach the surface of the cathode at a high speed. The high kinetic energy of the ions generates a lot of heat, melting the cathode surface.
1.4.2.4 Ejection of the Liquid Molten Material

At the end of the user specified discharge time, the EDM machine stops the current abruptly. As a consequence, the plasma channel collapses and so the pressure on the molten cathode and anode surface (caused by the plasma channel) drops suddenly. This makes the molten materials at both tool electrode and workpiece to boil violently and small droplets of liquid metal are ejected from the molten metal pool. The removed material is evacuated by the flow of the dielectric fluid. This is the main material removal process in EDM. The main part is removed by the sudden and intense boiling at the end of the discharge.

The thermal model established by Snoeys, et. al., [23] allowed calculating only about 10% of the material that gets overheated due to the pressure drop at the end of the discharge. So only those 10% molten material may be evacuated by bulk boiling; some 90% will re-solidify at the workpiece surface yielding the white layer or melt zone as observed in the EDM process. The ejection of molten material caused by a single discharge creates a kind of explosion. The result of successive discharge is the surface of overlapping craters.

The evolution of voltage and current during one discharge is as shown in Fig. 1.5. In the beginning, the open circuit voltage is applied between electrode and workpiece. Due to reorganization of the dielectric, which takes the ignition delay time $td$ the voltage breakdown occurs to about 20 or 25V and the plasma channel is created, so current starts to
flow. As well the value $i_e$ as the time $t_e$ of the current can be chosen by the user. After the discharge time, the current is stopped by the EDM machine and some time is waited to allow the dielectric to reorganize and deionize. Then a new cycle is started. This continues until the workpiece is finished.

**Fig. 1.5** Schematic diagram of current and voltage evolution during one discharge (Courtesy: Spur 1993)

Some other electrical parameters are introduced in Fig. 1.5. The main parameters are summarized below:
1.5 EDM PROCESS PARAMETERS

Parameters in EDM can be classified into three categories: control parameters, process result, and sensing parameters. Chien Nan Yang [24]. The complete set of parameters is machine dependent. Different EDM machines have different set of parameters due to the difference in their designs. Control parameters include those related to the workpiece, tool electrode, generator, servo system, dielectric system, and the NC unit. Some of these parameters are fairly straight-forward and require no further explanation. EDM units utilize sophisticated software that set certain parameters according to machining applications, material properties, geometry and design, and the desired surface finish or machining time. A list of parameters usually found on most EDM machines is given in Table 1.1 (refer to page -27). Table 1.2 (refer to page -28) describes both the dependent and independent variable in the process. Control parameters and process results are discussed below:

1.5.1 Generators

Generator or power supply provides electrical energy in the form of pulses to the working gap. Generators can be roughly classified into two categories: RC-relaxation generators and static pulse generators. RC-relaxation generators use charging circuitry to charge parallel capacitors to the gap. Discharges occur when the voltage across the gap reaches a certain level. The drawback of RC-relaxation generators is difficult to
control over the energy on a commercially available wire-cut static pulse
generators use transistorized power supply to generate the voltage pulses.
They enable a better control over pulse generation.

The control parameters on generator are most important because they directly determine the power applied to the working gap.

a) Open-circuit voltage
Open-circuit voltage specifies the voltage of applied pulses. It is not the voltage across the gap during electrical discharges. The latter is always about 15~25V.

b) Pulse duration or discharge duration
These parameters determine the length of the applied voltage pulses. Pulse duration, which is a setting on iso-frequent generators, sets the length of applied voltage pulses. During pulse duration, the lengths of ignition delay and discharge duration depend on the gap state. The actual discharge duration is not controllable. In iso-energetic generators, discharge duration can be set directly. Together with peak discharge current, pulse duration sets the amount of energy generated during a single electrical discharge.

c) Peak discharge current
The setting of peak discharge current on static pulse generators generally determines the number of power units connected parallel to the gap rather
than the exact current level. The larger peak discharge current means the higher power intensity during electrical discharge. Discharge current in wire-cut EDM machines never reaches the steady state level due to the short pulse duration. Therefore, in wire-cut EDM machines, the maximum level of current also depends on the discharge duration.

d) Pulse interval, Duty factor, or Pulse frequency
Pulse interval, duty factor, or pulse frequency determines the separation of pulses. Duty factor is defined as the ratio of pulse duration over pulse period. In machines with duty factor setting, pulse interval is set indirectly by setting pulse duration and duty factor. Pulse frequency is also used to set the pulse interval on some machines.

f) Polarity
It specifies the polarity of workpiece and tool electrode. Depending on the application, the polarity can be either way.

1.5.2 Servo System
The servo system controls the tool motion relative to the workpiece to follow the desired path. It also controls the gap width within such a range that the discharge process can continue. If tool electrode moves too fast and touches the workpiece, short circuit occurs. Short circuit contributes little to material removal because the voltage drop between electrodes is small and the current is limited by the generator. If tool electrode moves too
slowly, the gap becomes too wide and electrical discharge never occurs. Another function of servo system is to retract the tool electrode when deterioration of gap condition is detected.

1.5.3 Dielectric System

The dielectric liquid has important functions in cooling electrodes, flushing debris away from the gap, and increasing the power intensity of the discharge. The most widely used types of dielectric liquid are mineral hydro-carbon oil for sink-EDM and deionized water for wire-cut EDM. The dielectric liquid is constantly circulated through a filtering system, which removes the debris from the dielectric liquid and controls the conductivity of the dielectric liquid. The conductivity and the debris concentration of dielectric liquid have even larger effect on breakdown condition than the types of dielectric liquid.

The most important process results are related to material removal, surface integrity, and geometrical accuracy.

1.5.4 Material Removal

Material removal determines both machining rate and tool electrode wear. In sink-EDM, the material removal rate is defined as removed volume of material per unit time and specifies material removal on workpiece. The relative tool wear, defined as the volumetric ratio of material removal on tool electrode over that on workpiece, measures the material removal on
tool electrode. In wire-cut EDM, linear cutting speed specifies the machining rate. The linear cutting speed describes the relative movement of the wire with respect to the workpiece. It is related to the contour of the workpiece. Because the workpiece thickness has influence on the linear cutting speed, a better indication is the cutting speed. The cutting speed is the product of the linear cutting speed and the workpiece thickness. Wire consumption and wire breakage result from tool wear.

The ratio of material removal between electrodes depends on some of the control parameters. Current density has the greatest influence on power distribution, which determines the ratio of material removal between electrodes. Because the plasma channel expands during discharge duration, the pulse duration is the most important control parameter affecting the relative material removal rate between the electrodes. The anode has larger material removal with shorter pulse duration while the cathode has larger material removal with longer pulse duration. Besides pulse duration, parameters that cause decrease of current density can reduce the material removal of the anode, too.

1.5.5 Surface Integrity

The electrode surface machined by EDM can be characterized by geometrical shape of the surface, metallurgical and chemical characteristics, and mechanical properties of the superficial area. Geometrical shape of the surface includes surface roughness and crater
shapes. Surface roughness was reported to increase with discharge energy. The thermal action of the spark produces a surface layer that consists of resolidified layer on the top of heat-affected-zone. Metallurgical, chemical, and mechanical changes exist in this surface layer.

The electrical discharge machined surface is made up of three distinctive layers consisting of white layer/recast layer, Heat Affected Zone (HAZ) and unaffected parent metal. Lim, et. al. [25, 26] provided a review on the metallurgy of EDMed surface, which is dependent on the solidification behaviors 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. Since the white layer is the topmost layer exposed to the environment, it exerts a great influence on the surface properties of the workpiece. They also discovered the presence of micro-cracks and high tensile residual stresses on the EDMed surface caused by the high temperature gradient. 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.

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. 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.

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. As a result, it increases the MRR, reduces the TWR and improves the sparking efficiency producing a strong corrosion resistant EDMed surface. 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. Luo.Y.F [27] 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.

1.5.6 Geometrical Accuracy

There is a gap between the workpiece and the tool electrode during the EDM process. This gap as well as the tool wear makes the resultant machined workpiece shape different from the theoretical one. Such deviation needs to be compensated by undersize tool electrode and by setting the correct tool feed. The prerequisite of this approach is the knowledge about the actual gap width.
In wire-cut EDM, the actual machined shape deviated from the theoretical one because of the physical size of the wire and the gap. Variation of this deviation along the workpiece height also exists due to wire wear, wire vibration, and wire bending. Wire vibration results from unwinding the wire and the flushing of dielectric liquid. The force from sparking can cause the span of the wire to be slightly barrel-shaped. The effect of all types of deviation influences the accuracy especially when cutting corners or small radii. The wire bending and vibration can be counteracted by setting a sufficiently large wire tension and minimizing the distance between wire guides.
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Table 1.2 Dependent and independent process parameters in EDM

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</table>

Summary

An introduction is given to machining of Advanced Engineering Materials and Non-traditional machining processes. History and development of Electrical Discharge Machining (EDM) process and Basic principles of EDM process are discussed. Evolution of a single spark in the EDM process is illustrated. EDM input process parameters and performance characteristics are also discussed.