Chapter 1

Introduction

1.1 Background of the Research

In spite of the remarkable process capabilities of EDM, it has some deliberate weaknesses like, low material removal rates and poor surface quality. In the recent past, conventional machining processes were combined with non-conventional machining processes to develop hybrid machining process for achieving better machining characteristics. Electrical discharge surface grinding (EDSG) is one of the variants of hybrid machining processes that involves combining operations of conventional grinding and spark erosion machining. In conventional grinding of ductile materials tendency of clogging of chips to the wheel surface is high. Direct contact of abrasive grains with the workpiece surface causes an increase in surface temperature, which causes wheel loading and hence reduces the material removal rate (Koshy et al., 1997). Moreover during machining of composites, tool face load varies alternatively while interacting with matrix and the reinforcement. EDSG operation provides a solution to this machining problem with the contribution of abrasion assisted spark erosion machining. The electrical discharge surface grinding (EDAG) is a development in electrical discharge grinding (EDG) in which abrasive bonded tool electrode is used. The EDSG can be realized in three different grinding modes such as electro-discharge abrasive cut-off grinding, electrical discharge abrasive face grinding and electrical discharge abrasive surface grinding. From the past experimental findings it has been observed that the material removal rate and surface quality can be improved by the selection of input parameters (H. Aoyama, 1985).

There is a growing demand of industries for high strength to weight ratio materials for the fabrication of the mould and dies, automobiles and aircraft components. These materials are having high heat and wear resistance properties due that they are difficult to machine by the conventional machining processes. The development of competent machining system is required to cope up these challenges. The concept of hybrid machining system was introduced by the researchers to improve the material removal rate and surface quality of the machined surface for various kinds of advanced materials like
ceramics, cemented carbides, super alloys and composites (Koshy et al., 1997; Kozak and Rajurkar, 2000). The component processes in hybrid machining involve different kind of energies, mutually assisting each other to remove their independent limitations. The participative role of parameters associated with a single energy is partially responsible for the material removal during machining. Efforts are being made by the researchers to investigate the multiphysics phenomenon during the hybrid machining of materials. The benefit of participative role of energies helps to reduce the machining cost and life of the tool. The role of non-conventional machining parameters during machining helps in understanding the mechanism of hybrid machining processes.

1.2 Non-conventional machining processes

Due to global competition and customer demands, manufacturing industries are constantly facing the challenges of economic cost, customer lead-time, manufacturing cycle time, etc. (Sarwar and Haider). Efforts have been made to the machine the alloys and advanced materials through non-conventional machining operations (Lewis et al., 1996). The improved thermal, mechanical and chemical properties of advanced materials (super alloys, composites, and ceramics) have created impediments in easy machining of such materials by conventional machining processes namely turning, milling and drilling etc. This requires enhanced tool material properties as compared to workpiece. Moreover, machining by such methods involves higher machining cost and less precision. To resolve the present manufacturing requirements of advanced materials, non-conventional machining methods are now being adopted worldwide to reduce the manufacturing cost and for effective control over machining parameters. Non-conventional machining approaches are applied usefully in industrial applications for effective control and optimal selection of process parameters during machining (Aggarwal and Singh, 2005). These methods play a significant role in manufacturing automobile, defense and tool and die making industries. After achieving the merits of non-conventional machining methods, efforts are being made for cross-process innovations to improve the machining characteristics. Continuous efforts from the researchers are being made in the hybrid machining processes to inbuilt technological improvements in their machining characteristics. Different approaches from the researchers are suggested to improve these systems by systematic failure mode effect
analysis using intelligent techniques (Sharma et al., 2005). The development of newer machining methods has always been the endeavor of technocrats and scientists. The main theme behind such endeavors is the improvements in surface quality, reduction in machining efforts, precision machining and economic considerations. These requirements are fulfilled by the development of newer machining methods and advanced materials. In these machining methods, there is no direct contact between tool electrode and workpiece surface due to which machining forces are reduced and the requirement of harder tool material is eliminated (Jain, 2009; El-Hofy, 2013). The performance and life of the tool electrode are improved during machining of extremely hard materials due to non-contact of tool electrode and workpiece. These machining methods utilize the different kind of energies in a controlled manner during the machining. These machining techniques can be automated and programmed for the fabrication of complex components.

![Non-conventional machining processes](image)

**Figure 1.1: Non-conventional machining processes**

The complex shapes and fragile components can also be machined with minimum human intervention. These non-conventional machining processes can be categorized in reference to type of machining actions involved in removal of material from the workpiece surface. Figure 1.1 shows the classifications of non-traditional machining processes on the basis of three interactions namely mechanical, thermal and chemical or electrochemical.
1.2.1 Mechanical Processes

The material removal by mechanical processes involves shear, erosion and abrasion action. The shear mechanism involves a cutting tool as a source of energy and the machining operation is performed by direct physical contact of the tool electrode with the workpiece. During these processes abrasion on the work material is created by the flowing high velocity of abrasive particles or fluid. In Ultrasonic machining (USM) and water jet machining (WJM) machining, material removal occurs due to mechanical/abrasion (MA) action. The machining medium is solid particles suspended in abrasive media (abrasive slurry) in the former while high pressure fluid jet is employed in latter. The ability of cutting of fluid can be enhanced by introducing abrasives in the fluid in case of abrasive water jet machining process. The classification and components of mechanical interaction for non-conventional machining processes is shown in Figure 1.2.

![Diagram of Mechanical non-conventional processes]

Figure 1.2: Mechanical interaction based non-conventional machining processes (After El-Hofy, 2013)
1.2.2 Thermal Processes

These processes involve utility of localized intense heating for the melting and vaporization of material from the workpiece surface. Figure 1.3 shows the classification of thermal non-conventional machining processes with their components.

Figure 1.3: Thermal non-conventional machining processes (After El-Hofy, 2013)
The sources of energy used can be spark energy, during Electric Discharge machining (EDM) and Plasma Beam Machining (PBM), amplified light during Laser Beam Machining (LBM), electrons in case of Electron Beam Machining (EBM) or ions for Ion Beam Machining (IBM). Each process requires a different type of machining medium.

1.2.3 Chemical and electrochemical processes

These processes involve removal of material by the ion displacement. From these processes, chemical processes involve material removal by chemical dissolution (CD) whereas electrochemical processes use electrochemical dissolution for material removal. Chemical milling (CHM) and photochemical machining (PCM) are the examples of chemical machining. Electrochemical machining (ECM) uses the electrochemical dissolution action to remove material using ion transfer in an electrolytic cell. Figure 1.4 shows the classification of chemical and electrochemical machining processes.

![Diagram of Chemical and Electrochemical Processes](image)

Figure 1.4: Electrochemical and chemical machining processes (After El-Hofy, 2013)
Table 1.1: Classifications of advanced machining processes (After Jain, 2009)

<table>
<thead>
<tr>
<th>Type of Energy</th>
<th>Mechanism of material removal</th>
<th>Transfer media</th>
<th>Energy source</th>
<th>Machining Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Abrasion/Erosion</td>
<td>High velocity particles</td>
<td>Pneumatic/hydraulic pressure/ Mechanical Vibrations</td>
<td>AJM, USM, WJM</td>
</tr>
<tr>
<td>Thermo-electric</td>
<td>Fusion</td>
<td>Hot gases Electron plasma</td>
<td>Ionised material High voltage</td>
<td>IBM, PAM EDM</td>
</tr>
<tr>
<td></td>
<td>Vaporization</td>
<td>Radiation Ions stream</td>
<td>Amplified Light Ionised material</td>
<td>LBM PAM CHM</td>
</tr>
<tr>
<td>Chemical</td>
<td>Chemical dissolution</td>
<td>Reactive environment</td>
<td>Corrosive agent</td>
<td>CHM</td>
</tr>
<tr>
<td>Electrochemical</td>
<td>Ion displacement</td>
<td>Electrolyte</td>
<td>High Current</td>
<td>ECM, ECG</td>
</tr>
</tbody>
</table>

**Process names with used abbreviations**

<table>
<thead>
<tr>
<th>Process name</th>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AJM</td>
<td>Abrasive Jet Machining</td>
<td>IBM Ion beam machining</td>
</tr>
<tr>
<td>CHM</td>
<td>Chemical Machining</td>
<td>LBM Laser beam machining</td>
</tr>
<tr>
<td>ECG</td>
<td>Electrochemical Grinding</td>
<td>PAM Plasma machining</td>
</tr>
<tr>
<td>ECM</td>
<td>Electrochemical machining</td>
<td>USM Ultrasonic machining</td>
</tr>
<tr>
<td>EDM</td>
<td>Electric discharge machining</td>
<td>WJM Water Jet machining</td>
</tr>
</tbody>
</table>
Table 1.1 depicts a summary of the mechanism, transfer media and energy source involved in various non-conventional machining processes. These machining methods can also be classified on the basis of media used for energy transfer like high velocity particles, physical contact, reactive atmosphere, hot gases, ion and electrons etc., mechanism of material removal like abrasion, shear, ionic dissolution and spark erosion etc., and sources of energy like pneumatic / hydraulic pressure, high current and voltage, ionized gas etc.

A particular process found suitable under certain conditions may not be suitable for other conditions. Therefore, knowledge and experience is required for the selection of a particular process for a given manufacturing project. The factors that determine the use of particular process in manufacturing are physical parameters involved in the process, capability of machining different shapes, suitability to various types of materials, operational characteristics and economic aspects involved in the processes.

Technological improvements of non-conventional machining processes can be achieved by combining different physio-chemical action on the material being processed. The machining process so developed is called Hybrid Machining Processes (HMPs) (Kozak and Rajurkar, 2000). In particular, the unconventional machining actions such as mechanical, thermal or electrochemical can be combined with mechanical action of conventional machining. In order to completely understand the mechanism of hybrid machining processes based on thermal and mechanical action, the knowledge of component processes and their parameters must be required. The few processes belong to hybrid machining category are Electro Chemical Spark Machining (ECSM), Abrasive Electrical Discharge Machining (AEDM) (Singh and Yeh, 2012), Ultrasonic Electric Discharge Machining (UEDM) and Abrasive Electro-chemical Discharge Machining (AECDM).

1.3 Electrical discharge machining

The inception of Electrical Discharge Machining (EDM) starts from World War I and II when B.R Lazarenko and N.I. Lazarenko the two Russian scientists invented the first relaxation circuit (RC) for EDM. They have developed a controlled process of machining difficult to machine materials by melting and vaporization. After many attempts, it has been concluded that erosion can be precisely controlled in the presence of the dielectric medium. Thereafter the effectiveness of EDM process was enhanced by using pulse generators,
introducing planetary and orbital motions, computer numerical control (CNC) and adaptive control systems. After the successful economical and precision benefits of EDM in manufacturing industry, wire EDM was introduced in 1970s to enhance the cutting capability of EDM towards newly developed material. These materials have more strength, toughness as well as wear resistance properties. The research initiatives by the past researchers enhanced the machining speed of EDM by 20 times and reduced the machining cost up to 30 percent with improvement of surface roughness up to 15 times (El-Hofy, 2013). EDM has been widely used in manufacturing industries to produce dies and molds. It is also used for finishing parts for aerospace and automotive industry and surgical components (Ho and Newman, 2003). EDM does not make direct contact between the tool electrode and the workpiece where it can remove mechanical stresses, chatters and vibration problems during machining. Any conductive material can be machined irrespective of its hardness and toughness (Ramasawmy and Blunt, 2004).

1.4 Mechanism of material removal in EDM

EDM, a thermoelectric process, utilizes heat energy of electrical sparks to remove material from the workpiece. In this process, tool electrode and workpiece material should be conductive. This process involves the removing of material from the surface of a workpiece by means of a series of repeated electrical discharges between the tool electrode and the workpiece in the presence of a dielectric fluid (Luis et al., 2005). During the start of operation, the tool electrode moves toward the work piece until the discharge gap is small enough so that the impressed voltage is sufficient to ionize the dielectric fluid (Bojorquez et al., 2002). The short duration discharges are generated in the discharge gap, which separates tool electrode and workpiece. The material is removed with the erosive effect of the electrical discharges from tool electrode and workpiece by melting and evaporation (Marafona and Chousal, 2006). The process of generation of erosive spark and formation of the plasma channel between tool electrode and workpiece is shown in Figure 1.5 (a-b). A passage of flow of electrons from the tool electrode to the workpiece is developed, which is called a plasma channel. When the pulsating direct current supply of 20,000-30,000 Hz frequency is turned off the sudden collapse of the plasma channel takes place (Krar and Check, 1997). This causes a rapid drop of temperature and allowing the dielectric fluid to
penetrate into the plasma channel and flush out the molten material in the form of debris from the discharge gap (Ho and Newman, 2003).

Figure 1.6 shows the three kinds of layers developed on electro-discharged machined components. If molten material from the workpiece is not adequately flushed out quickly, it will resolidify and harden due to the cooling effect of the dielectric fluid and gets adhered to the machined surface. This thin layer is called recast layer. It is extremely hard, brittle and porous and may contain micro cracks. Beneath the recast layer, a HAZ is formed due to rapid heating and quenching cycles during EDM (Choudhary et al., 2010 : Jain,
The effect of heating-cooling cycle on the machined surface and diffused material during machining are the main reasons for the existence of this zone. Thermal residual stresses due to the temperature gradient, grain boundary weaknesses, and grain boundary cracks are some of the widely seen characteristics of this zone. Conversion zone (or converted layer) is identified below the HAZ and is characterized by a change in grain structure from the original structure (Jain, 2009).

![Schematic diagram of three kinds of layers on an EDMed component](After Jain, 2009)

Figure 1.6: Schematic diagram of three kinds of layers on an EDMed component (After Jain, 2009)

Figure 1.7 shows white recast layer of 11µm developed after aluminum powder mixed EDM of W300 die steel machined using distilled water as a dielectric fluid at negative tool polarity of tool electrode (Syed and Kuppan, 2013). The thickness of recast layer reported to be increased with increase in value of current and pulse on-time (Amorim and Weingaertner, 2007). Figure 1.8 depicts the recast layers at I=64A and I=4A developed due to electrical discharge machining of copper-beryllium alloy at rough and finish modes conditions. It was concluded by authors that the depth of recast layer, phase transformation zone and conversion zone increases with an increase in discharge current and pulse on-time. The observed depth of recast layer is 5µm for finish mode and 70µm for rough mode conditions. The recast layer developed on the machined surface can be removed by applying magnetic abrasive finishing, etching or grinding.
Figure 1.7: Recast layer on W300 die steel machined with distilled water at I=12A, \( T_{on}=220\mu s \) at negative polarity of tool electrode (After Syed and Kuppan, 2013)

Figure 1.8: Traverse section of CuBe samples after EDM (a) rough machining under I=64A, \( T_{on}=300\mu s \), \( \tau=0.5 \) depicting 70\( \mu m \) thick dark recast layer (b) finishing under I=4A, \( T_{on}=30\mu s \), \( \tau=0.5 \) depicting a 5\( \mu m \) very thin recast layer (After Amorim and Weingaertner, 2007)
1.5 Components of EDM

A schematic diagram of electrical discharge machining is shown in Figure 1.9. EDM is a non-conventional process and the equipment used for electrical discharge machining is available in various configurations ranging from manually operated to highly sophisticated computer controlled. Regardless of its complexity EDM equipment consists of four major sub-assemblies that include following

- Power Supply
- Dielectric System
- Electrode
- Servo-System

1.5.1 Power Supply

It is an important part of EDM setup. The main function is to transform alternating current (AC) from main power supply into the pulse direct current (DC) which is required to produce a spark at the machining gap. The other main function that is performed by EDM power supply system is sensing the gap voltage between the electrode and workpiece.

1.5.2 Dielectric System

The dielectric system of EDM consists of dielectric fluid, delivery devices, pumps and filters. Dielectric fluid is a very crucial part of the EDM process. The dielectric fluid is used to cool and flush resolidified particles from the discharge gap.
The main functions, that a dielectric fluid can perform, are:

- It acts as an insulator between the electrode and workpiece.
- It serves as a coolant to draw away the small amount of heat generated by the sparks.
- It acts as a flushing medium to remove the metal by-products from the cutting gap.

The most popular fluids that are commonly used are hydrocarbon oil, silicon-based oils and deionized water because they offer properties like high viscosity and high electrical resistance.

1.5.3 Electrodes

EDM tool electrodes are fabricated in a variety of forms such as, solid type of required profile, coated wire, tube-shaped, or bar stock, depending upon type of electrode materials used and the application.

The basic characteristics required in electrode materials are:

- The tool electrode should have a higher electrical conductivity so that electrons are emitted more rapidly and hence there is less scope of electrical heating
- EDM tool electrode should have higher thermal conductivity to avoid rise in high local temperatures due to faster heat conducted by the tool electrode and hence corresponds to lesser tool wear.
- Density of tool electrodes should be high so that for the same heat load, there would be less volume of material removal from tool which leads to lesser dimensional loss and inaccuracy.
- The melting point of tool electrodes should be high. This leads to lesser tool wear due to heat for the same heat load.
- Electrode material should be cheap and easily available.

1.5.4 Servo System

The servo system of EDM works on signal generated by gap voltage sensor system in the power supply, and it controls the in-feed of the electrode or workpiece to match the MRR precisely. When there is gap bridged between the electrode and workpiece it is sensed by gap voltage sensor system and then signal is sent to servo system and servo system reacts by reversing direction until the dielectric fluid flushes the gap clear. When the gap is clear, the in feed resumes and cutting continues. If the flushing technique being
used is insufficient in removing the process by-products from the machining gap that result in extremely long machining cycles.

1.6 Applications of EDM

Modern EDM machines are capable of producing intricate shapes and are well equipped with special functions like computerised control for regulating the cutting path of the wire and its cutting angle with respect to the workpiece plane, multi-tool heads for cutting two parts simultaneously and safety features like automatic self-threading in the case of wire breakage, controls for preventing wire breakage and programmed features to optimize the machining operations.

The electrical discharge machining capabilities can be used for the manufacture of tools having complicated profiles. This process provides cost-effective benefit toward the fabrication of intricate mold cavities, wire drawing and extrusion dies, forging dies and stamping tools. It has been enormously used for machining of exotic materials used in aerospace and automotive industries such as refractory metals, hard carbides, and hardenable steels. Figure 1.10 shows the typical industrial applications of EDM process.

Figure 1.10: Industrial applications of EDM (After Web, 2014)
Some of the distinctive applications of EDM are:
1. Fine cutting using thread shaped wire electrode
2. Drilling of micro holes
3. Thread cutting
4. Helical profile milling
5. Rotary forming
6. EDM can fabricate delicate components like copper parts for fitting into the vacuum tubes.
7. This process can be effectively used to machine all electrically conducting metals and alloys regardless of their strength, hardness and toughness.

1.7 Advantages and Limitations of EDM

The EDM process has the following advantages.

- There is no physical contact between job and tool so workpiece is not subjected to any mechanical deformation even slender and fragile jobs can be easily machined.
- There is no heating of the material even though the material is removed by thermal effects.
- Complex profiles on hard materials can be shaped easily to a high degree of precision and surface finish.
- EDM process can be applied to all electrically conductive materials irrespective to the physical and metallurgical properties of the work material.
- The whole process can be automated and it needs minimum human attention.

Despite the promising results of EDM, it suffered from serious drawbacks like low machining rate, instability, and rough machining surfaces. In the process of EDM die-sinking fixed tool electrodes are used to machine die cavities or rotary device is used in addition to its inbuilt functions to control the electrode’s path during EDM profiling. However, a large surface with appreciable flatness is difficult to machine by this machining process. On the other hand large surface can be easily machined by the wire-cut electrical discharge machining (WEDM). The vibrations of the wire electrode during electrical discharges appear to be an inevitable problem, which is a dominant aspect in the machining of flat surfaces.
1.8 Variants of EDM

Electrical discharge machining has reached its developing stage with a number of its variants successfully implemented by the industries. These variants are based on different configurations with respect to tool and workpiece to fulfill the manufacturing demands of the industries. These variants are now being established as independent machining processes with their controllable input machining parameters. Efforts from the researchers are now being made to develop these variants by enhancing their machining characteristics during machining of hard to machine materials. Some popular variants of EDM are wire EDM (WEDM), EDM Milling, Rotary EDM (REDM) and Rotary Disk Electrode (RDE) (EDM).

a) **Wire EDM (WEDM):** In the wire EDM, material is removed by the erosive effect of electrical discharges occurs between wire electrode and workpiece in the presence of dielectric fluid. This wire is usually made up of brass and copper which is being fed continuously during the machining process. Fig. 1.11 shows the schematic diagram of WEDM. This variant of EDM is used in industries for the cutting of tool and dies steels for the manufacturing of dies and molds. This process is also used to machine super hard materials such as polycrystalline diamond (PCD) and cubic boron nitride (CBN) blanks and other composite materials used in aerospace and automobile industries.

![Fig. 1.11 Schematic diagram of WEDM](image-url)
b) **EDM Milling:** EDM Milling is another variant of EDM, in which rotary contour shaped tool electrode is used for the milling operation. The schematic diagram of EDM milling is shown in Fig. 1.12. Rotary as well as planetary motions can be imparted to the tool electrode to machine the workpiece in step operation. This process is used on die sinking setup for the machining of step grooves and profiles during the machining operation.

![Fig. 1.12 Schematic diagram of EDM milling (After Web, 2014)](image)

c) **Rotary EDM:** In rotary EDM, rotational movement is imparted to the tool electrode immersed in a dielectric fluid during the machining process. In this process cylindrical solid or hollow tube electrode can be used to machine the materials. The rotary motion is an additional motion imparted to the tool electrode as compared to die-sinking EDM. Cylindrical groves, tapered, curved and enlarging of pre-drilled holes can be made by this process. To the same machining process, planetary motion in addition, can be given to the tool electrode for grooving operations.

d) **Rotary Disk Electrode (RDE) EDM:** Machining by rotary disk electrode EDM involves the use of circular metal disk tool electrode (copper or brass) for the cutting operation. The working principle of RDE EDM is shown in Fig. 1.13. The material is removed by the erosive electrical discharges occurred between rotary disk electrode and workpiece in the presence of dielectric fluid during the machining process. Material removal rate and cutting efficiency are enhanced due to fast removal of debris.
from the machining gap due to the rotation of tool electrode. Titanium alloys and High Carbon High Chrome Steel can be effectively machined by this process. Studies on rotary disc EDM concluded that aspect ratio of disc and peak current significantly affect the machining characteristics of the process (Singh and Pandey, 2013; Singh and Pandey, 2014).

In the present work rotary EDM was used to develop EDSG set up for the experimentation. Next section describes the process parameters of REDM out of which some of the parameters were selected in EDSG experimentation.

1.9 Rotary EDM process parameters

REDM process has input and response parameters. These process parameters can be grouped into two categories i.e. electrical and non-electrical parameters while response parameters being Material Removal Rate (MRR), Electrode Wear Rate (EWR) and Surface Roughness (SR). The levels of electrical and non-electrical parameters play a significant role in optimizing the performance measures of the process.

Many attempts have been made by the researchers for the optimization of these process parameters such as peak current ($I_p$), pulse on-time ($T_{on}$), pulse off-time ($T_{off}$) and open circuit voltage ($V$) and rotational speed to minimize SR and the EWR and simultaneously improving MRR. MRR is higher the better type of the machining
characteristic, whereas SR and EWR belong to ‘lower the better type’ characteristic. The rotary electrical discharge machining parameters are classified in Figure 1.14. The electrical parameters related to pulse wave form are depicted in Figure 1.15.

1.9.1 Electrical Parameters

- **Gap Current**: The gap current represents the amount of power expended in discharge generation and is regarded as most considerable process parameter. The current increases until its value reach a predetermined level during pulse on-time, which is known as peak current. Surface area of cut governs peak current. This is the most significant parameter because the surface generated is a copy of tool electrode and the excessive wear of tool electrode at higher amperage may hinder the accuracy of the machining. New improved electrode materials like graphite can be used at high currents without causing much damage to the machined surface (Kansal et al., 2005).

![Figure 1.14: REDM process parameters (After Garg et al., 2010)](image)

- **Gap Voltage**: Discharge voltage is associated with spark gap and the breakdown strength of the dielectric fluid. The gap voltage increases before electrical discharge unless ionization route is developed between workpiece and tool electrode. Once the
flow of current starts, the voltage drops and stabilizes at the working gap level. Hence at higher settings of voltage increase in gap occurs, this in turn improves the flushing conditions and stabilizes the cut.

- **On-time** ($T_{on}$): It is the period of sparking time measured in microseconds. During this duration, the current is allowed to flow through the electrode towards the workpiece. The material removal rate of the workpiece is directly proportional to the amount of energy released during the on-time and is also defined as discharge duration during which sparks are generated at a particular frequency.

![Figure 1.15: Pulse wave form of Pulse Generator (Amorim and Weingaertner, 2002)](image)

- **Pulse Interval** ($T_{off}$): During off-time the pulse rests and the re-ionization of the dielectric fluid take place that affects the pace of the operation significantly. The off-time also manages the stability of the process. An insufficient off-time may lead to inconsistent cycling and causes retraction of the advancing servo system which slows down the machining.

- **Electrode Gap** (spark gap): It is the distance between the electrode and the workpiece during machining. An electro-mechanical and hydraulic systems are used to maintain the average gap voltage (Pandey and Singh, 2010). In order to achieve satisfactory performance and gap stability, an appropriate machining gap should be maintained.

- **Duty Cycle**: It is a percentage of the on-time relative to the total cycle time during machining. This parameter can be defined as the ratio of on-time to the total cycle time (on-time plus off-time). It indicates the degree of efficiency of the operation. With the increase of duty factor, pulse on-time increases, due to which MRR increases (Pandey and Singh, 2010).
\[
Duty\ Cycle = \frac{T_{on\ time}}{T_{on\ time} + T_{off\ time}}
\]

- **Polarity**: It may be positive or negative connected to the tool electrode or work material. Polarity can affect the processing speed, surface finish, tool wear and stability of the EDM operation. Some studies show an increase in MRR when the tool electrodes are connected with positive polarity (+) than at negative terminal (-). This may be due to the transfer of energy during the charging process being more in this condition of machining. The negative polarity is more desirable as compared to positive for most of the materials (Pandey and Singh, 2010; Chow et al., 1999).

1.9.2 Non electrical parameters

- **Rotation of Tool Electrode**: It is the rotational speed of cylindrical or disc shaped tool electrode measured in revolution/minute. Generally, the axis of rotation of tool electrode is normal to the workpiece surface, and it depends upon the shape of the tool electrode. The increase in speed of the tool electrode generates higher centrifugal force that causes faster removal of debris from the machining gap which improves machining stability and performance (Soni and Chakraverti, 1994).

- **Injection Flushing**: Flushing clears eroded particles and debris from the machining gap for the smooth operation and improved surface finish of the machined component. The pressurized dielectric fluid flushes out the particles from the machining gap more efficiently, and the removal of debris from the dielectric fluid is caused by the filtering unit of the EDM. There are different ways of flushing for different tool work combinations. (Wong et al., 1995).

- **Tool Geometry**: Tool geometry is related to shape of the tool electrodes i.e. square, rectangle, cylindrical, circular etc. The ratio of length/diameter of any shaped material. In case of rotating disk electrode the ratio becomes thickness/diameter. The tool having less aspect ratio gave a higher value of EWR. Thus with increasing the size of tool electrode higher performance of EDM can be achieved (Singh et al., 2007).

- **Tool Material (Electrode)**: Engineering materials having higher thermal conductivity and melting point can be used as tool material for EDM process. Copper, graphite,
copper-tungsten, silver tungsten, copper, graphite and brass are some of the tool electrode materials (electrode) used in EDM (Boothroyd, 1989)

1.9.3 Performance Measures of REDM

- **Material Removal Rate (MRR)**: It is defined as the amount of material removed from the workpiece surface per unit time. The MRR can also be expressed as the weight of material removed from the workpiece over machining time in minutes.

\[
MRR \left( \frac{mm^3}{min} \right) = \frac{Workpiece \ weight \ loss \ (g) \times 1000}{Density \ (g/cm^3) \times \ machining \ time \ (min.)}
\]

- **Electrode Wear Rate (EWR)**: It can be determined as material removed from the tool electrode per unit time. The EWR can also be calculated by using the weight loss from the tool electrode over the time of machining.

\[
EWR \left( \frac{mm^3}{min} \right) = \frac{Tool \ weight \ loss \ (g) \times 1000}{Density \ (g/cm^3) \times \ machining \ time \ (min.)}
\]

- **Surface Roughness (SR)**: It is expressed as the measurement of irregularities developed on the material due to machining. It is also expressed as average surface roughness denoted by Ra. The parameters that affect surface roughness are gap current, \(T_{on}, T_{off}\), and gap voltage (Pradhan and Biswas, 2009). SR measurements of machined surfaces reveal the effect of EDM parameters on surface integrity. Theoretically, Ra is represented as deviation from the mean value.

\[
R_a = \frac{1}{L} \int_0^L h(x) \, dx
\]

Where \(h(x)\) is the value of the roughness profile and ‘L’ is evaluation length.

1.10 Hybrid machining processes

The hybrid (cross) machining processes make use of combined or mutually enhanced advantages of constituent processes (Kozak and Rajurkar, 2000; Kozak and Rajurkar, 2010). An advanced material plays an imperative role in modern manufacturing industries like aerospace, automotive, tool & die making industries (Ho and Newman, 2003
The improvement in their properties like strength, heat, wear and corrosion resistance provides enormous economic benefits to these manufacturing industries for their enhanced product design and performance. It has already been reported in the literature that conventional machining processes are often ineffective in machining of these materials. To meet these challenges, the improvement in the performance of non-conventional machining processes is continuously going on (Kansal et al., 2007; Kumar and Davim, 2011). The latest development in this regard is being achieved by combining the different non-conventional machining processes with conventional ones. In hybrid machining, one of the energy is taken as the source of external energy into another. As a result, the limitation of one process becomes the advantage of another process.

The performance characteristics of hybrid machining processes (HMP) are different from those of component processes, when performed separately. To achieve higher performance, combinations of physical and chemical processes have been developed by the researchers. For example, productivity of electrochemical discharge machining (ECDM), which involves occurrence of electrical discharges in the electrolyte, is 5 to 50 times greater than individual processes (Kozak and Ocezoś, 2001; McGeough et al., 1983) (Jain, 2009). In comparison to ECM, Electrochemical grinding (ECG) involves a combination of ECM and mechanical grinding, which provides better economy in manufacturing of carbide cutting tools (El-Hofy, 2013). Due to the use of the combined effect of energies, machining cost of the grinding wheel reduced to 80 % and the labour costs have been reduced to 50 % (Benedict, 1987). Electrical based hybrid machining processes have been developed to remove the limitations of ECM and EDM. These processes required conductive tool and workpiece electrically. Hybrid machining processes such as electrochemical spark machining (ECSM) and electrochemical arc machining (ECAM) are the processes in which material is removed by the combined effect of electro-chemical action and thermal effect. These processes are suitable for the machining of electrically conductive and non-conductive materials. (Jain et al., 1991; Gautam and Jain, 1998). These processes are also effectively used by the manufacturing industries in machining of soda lime, borosilicate glass, quartz, glass fiber, reinforced plastics and ceramics (Jain and Chak, 2000). Moreover, these processes can be used for wire cutting, hole drilling and die sinking of composites and conductive ceramics (Gautam and Jain, 1998). Materials with tensile strength above
1500 N/mm$^2$ and high heat resistance alloys can be effectively machined with ECAM and ECSM processes. Higher material removal rates can be achieved up to 104 mm$^3$/min with an accuracy of 0.04-0.02 mm and surface roughness of (1.25-2.5 mm) Ra. (Kozak and Oczoś, 2001). The abrasive hybrid machining processes are developed by combining abrasive machining with nonconventional machining processes like EDM, ECM and USM. Abrasive hybrid machining processes are also gaining interest in the industries due to their enhanced machining capabilities. They can be classified into three main groups such as Abrasive Electrical Discharge Machining (AEDM) (Singh and Yeh, 2012), Abrasive Electrochemical Machining (AECM) (Kozak and Oczoś, 2001) and Abrasive Electro-chemical-Discharge Machining (AECDM). The effect of abrasive powder mixed dielectric fluid during EDM was studied by the researchers. The performance characteristics of (Abrasive Powder Mixed) APM-EDM of 6061Al/Al$_2$O$_3$/20p composites (AMCs) was determined using multiple optimization approach, i.e. gray relational analysis and Lenth’s method (Singh and Yeh, 2012). In another study, the effect of current, powder concentration and electrode diameter on MRR and TWR was investigated. The powder mixed EDM (PMEDM) of Al/10%SiC was conducted by Kansal et al. to investigate the effect of metal powders on machining characteristics. The study reveals that aluminium powder suspended in the dielectric of EDM significantly improves the MRR and SR (Kansal et al., 2006a; Kansal et al., 2007). In abrasive electrochemical grinding, mechanical action (abrasion) is imparted by metal bonded abrasive tool electrode. During this process energy consumption and tool wear rate get reduced due to the use of combined form of energies in hybrid machining process. Increase in process productivity is due to combined micro cuttings and electrochemical dissolution in AECG process. The variety of materials such as carbides, creep resisting alloys such as Inconel, Nimonics, titanium alloys, metal matrix composites such as PCD-Co, Al-SiC, Al-Al$_2$O$_3$ can be effectively machined by Abrasive Electrochemical Grinding process (AECG) (Kozak and Oczoś, 2001). With these kinds of processes, 90% of the material is removed by electrochemical phenomenon and rest is machined by abrasion (Jain, 2009). Table 1.2 shows the classification of hybrid machining processes and their energy components based upon their energy interactions.
### Table 1.2: Classification of hybrid machining processes (After Yadava, 2001)

<table>
<thead>
<tr>
<th>Major Source of Energy</th>
<th>Process</th>
<th>Combination of Energy Sources</th>
<th>Mechanism of Material Removal</th>
<th>Tool</th>
<th>Transfer Media</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>Ultrasonic Assisted Electrical Discharge Machining (UAEDM)</td>
<td>Thermal and Ultrasonic Vibration</td>
<td>Melting &amp; Evaporation</td>
<td>Sonotrode</td>
<td>Dielectric fluid</td>
</tr>
<tr>
<td>Thermal</td>
<td>Ultrasonic Assisted Laser Beam Machining (UALBM)</td>
<td>Thermal and Ultrasonic Vibration</td>
<td>Melting &amp; Evaporation</td>
<td>Laser beam</td>
<td>Air</td>
</tr>
<tr>
<td>Major Source of Energy</td>
<td>Abrasive Electrical Discharge Machining (AEDM)</td>
<td>Thermal and powder mixed dielectric</td>
<td>Melting &amp; Evaporation</td>
<td>Metal Tool electrode</td>
<td>Powder mixed dielectric fluid</td>
</tr>
<tr>
<td>Electrochemical and Chemical</td>
<td>Electrochemical Spark Machining (ECSM/ECAM)</td>
<td>Electrochemical and Thermal</td>
<td>Melting and Evaporation</td>
<td>Electrode</td>
<td>Electrolyte</td>
</tr>
<tr>
<td>Electrochemical and Chemical</td>
<td>Electrochemical Abrasive Grinding (ECAG)</td>
<td>Electrochemical and Mechanical</td>
<td>Electrochemical dissolution and abrasion</td>
<td>Metal bonded abrasive wheel</td>
<td>Electrolyte</td>
</tr>
<tr>
<td>Electrochemical and Chemical</td>
<td>Laser Assisted Electrochemical Machining (LAECM)</td>
<td>Electrochemical and Thermal</td>
<td>Electrochemical dissolution and heating</td>
<td>Electrode</td>
<td>Electrolyte</td>
</tr>
<tr>
<td>Electrochemical and Chemical</td>
<td>Ultrasonic Assisted Electrochemical Machining (UECM)</td>
<td>Electrochemical and Ultrasonic Vibration</td>
<td>Electrochemical dissolution</td>
<td>Sonotrode</td>
<td>Electrolyte</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Brush Erosion Dissolution Mechanical Machining (BEDMM)</td>
<td>Electrochemical Thermal, and Mechanical</td>
<td>Electrochemical, Melting and Mechanical Rupture</td>
<td>Rotating Metal brush</td>
<td>Water glass solution in water</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Laser Assisted Chemical Etching LAE</td>
<td>Chemical and Thermal</td>
<td>Chemical dissolution and heating</td>
<td>Mask</td>
<td>Etchant</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Electrical Discharge Abrasive Grinding (EDAG)</td>
<td>Mechanical and Thermal</td>
<td>Melting, Evaporation and abrasion</td>
<td>Metal bonded abrasive wheel</td>
<td>Dielectric fluid</td>
</tr>
<tr>
<td>Laser/Plasma Assisted Turning (LAT/PAT)</td>
<td>Mechanical and Thermal</td>
<td>Shearing and Heating</td>
<td>Turning tool</td>
<td>Air</td>
<td></td>
</tr>
<tr>
<td>Mechanical</td>
<td>Ultrasonic Gas Atomization (UGA)</td>
<td>Mechanical and Ultrasonic Vibration</td>
<td>Abrasion</td>
<td>Sonotrode of abrasive wheel</td>
<td>Coolant</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Ultrasonic Assisted Turning (UAT)</td>
<td>Mechanical and Ultrasonic Vibration</td>
<td>Shearing</td>
<td>Turning tool</td>
<td>Air</td>
</tr>
</tbody>
</table>
Figure 1.16 shows the interactions of mechanical, chemical, electrochemical and thermal actions in hybrid machining processes. The introduction of abrasion effect in ECM develops electrochemical grinding (ECG). Similarly, laser energy can also be used with electrochemical machining to develop laser assisted electrochemical machining. Mechanical interaction can also be used to build ultrasonic assisted electrochemical machining. Kozak and Rajurkar reported that the mechanical interaction with the workpiece material improves the anodic dissolution conditions by mechanical depassivation of the surface (Kozak and Rajurkar, 2000). These mechanical vibrations improve the electrolyte flushing which causes increased material removal rates. The triplex action can also be used during machining by integrating mechanical grinding with electro-discharge erosion (EDE) and electro-chemical dissolution (ECD) to develop electro-chemical discharge grinding (ECDG) set up. Another category of hybrid machining process is electro-discharge abrasive grinding (EDAG) that involves a combination of EDM and conventional grinding. In this process metal bonded diamond grinding wheel is used with EDM process. This process involves simultaneous spark interaction with abrasion due to abrasive grains which improve the machining characteristics.

Figure 1.16: Hybrid machining processes (After El-Hofy, 2013)
These spark interactions thermally soften the workpiece surface and thus minimizes the grinding forces with abrasion action. The life of the grinding wheel is enhanced due to spark interactions and minimum grinding forces. The abrasion action involved in the process improves material removal rate and surface finish. The electro-discharge diamond grinding (EDDG) can be used for the machining of advanced engineering materials like polycrystalline diamond (PCD), polycrystalline cubic boron nitride (PCBN) and electrically conductive ceramics (Kozak, 2002). The experimental study of self-dressing mechanism of electrical discharge abrasive grinding was conducted to determine the effects of current, pulse on-time and wheel speed on process performance (Kozak, 2002). The study reveals that an electro-erosion process can be used for profiling of super hard metal bonded abrasive wheel. The specific energy required in electro-discharge abrasive grinding is found to be less as compared to electrical discharge grinding. The wheel speed and current are found to be most influential factors that affect the performance of the EDAG process (Yadav et al., 2008).

In the present study, optimization of process parameters of electric discharge surface grinding (EDSG) has been carried out during the machining of AISI D2 die steel and 6061Al/10%Al₂O₃p composite. The reason for choosing the same is to study the different machining mechanism of these materials during EDSG. In the previous research work, no detailed investigations have been made on these materials by selecting two machining parameters such as APS and APC.

1.11 Electrical Discharge Surface Grinding

The EDSG process has a different machining mechanism as compared to EDM and conventional grinding. It has a controlled electric discharges function assisted by mechanical grinding. If EDDG is carried out in surface grinding mode where whole workpiece and a part of the grinding wheel/composite tool electrode are completely dipped in dielectric fluid, the process is called as EDSG. The contribution of grinding and electrical discharge in EDSG, is illustrated in Figure1.17. There are two basic configurations (Figure 1.17 (a) and (b)) by which the combination of grinding with EDM, can be realized. The first option utilizes a cylindrical metal matrix composite (MMC) tool electrode made up of a metal matrix reinforced with abrasive particulates fitted in the tool
holder of a rotary spindle attachment to the conventional EDM machine. In the second case, a metal-bonded abrasive wheel can be used in place of cylindrical composite tool electrode with suitable rotary attachment. The axis of rotation is different for two configurations. The workpiece is fitted on the holding fixture in the machining tank and the vertical feed of the rotary tool is controlled by a servo mechanism of an EDM machine. The appropriate flushing technique can be used to ensure efficient and quality machining.

The removal of material in EDSG takes place by combined action of erosive discharges and grinding of the resolidified layer of the workpiece. The mechanical interaction due to abrasion helps in faster removal of material from a workpiece surface. With this kind of unconventional setup, the removal of nonconductive particles with conductive electrodes is also possible (Kozak, 2002; Yan et al., 2000).

1.12 Working principle and mechanism of material removal in EDSG

The principle of EDSG process is being illustrated in Figure 1.17 (a). When a suitable voltage is applied between the two electrodes (workpiece and tool) of EDM, the spark is generated between them. The grinding action along with the electric sparks starts when the abrasive grits in the rotary electrode come in contact with the workpiece surface. This contact does not result in short circuiting between tool and workpiece because of nonconductive nature of abrasive grits. As a result, the thermal interaction (erosive spark discharges) and the mechanical interaction (abrasion/grinding) removes the material from the surface of the workpiece. The mechanical interaction due to abrasion helps in faster removal of material from the workpiece surface. Thermal effect combined with mechanical grinding helps in removing the resolidified layer and debris produced during spark erosion process. Tool life is enhanced due to reduction in machining forces by spark erosion assistance.

Surface generated in EDSG process is smoother as compared to EDM due to grinding of resolidified layer that otherwise get deposited on workpiece surface due to surface tension effect and faster cooling rates in EDM process (Kozak, 2002; Shu and Tu, 2003). The effect of grinding increases with an increase in rotational speed of the tool electrode and hence, contributes to increased MRR (Yadava, 2008).
The mechanism of material removal in EDSG process is shown in Figure 1.18. During machining, the abrasive grains help the process in achieving a more metal removal rate with the assistance of electrical spark energy. During the EDSG operation, the protruded abrasive grains remove the resolidified layer by reaching the base matrix and thus enhance the life of machined components (Shu and Tu, 2003).

Figure 1.17: Experimental setup of EDSG process: (a) Composite (abrasive) tool electrode in EDSG (b) Metal bonded abrasive wheel in EDSG set up
Figure 1.19 represents the relation between the protrusion height of the abrasive with the size of the abrasive in EDSG process (Shu and Tu, 2003). The protrusion height is the extended length of the abrasive from the base metal matrix. As the size of the abrasive particulate increases, the protrusion height also increases. Thus, the contribution of abrasive particle toward abrasion increases with an increase in protrusion height. From Figure 1.19, it can be observed that larger size abrasives approach the surface of the workpiece prior to smaller abrasives.
These abrasives can move beneath the upper surface of the workpiece and removes recast layer from the base matrix developed due to spark erosion. One of the significant benefits of the process is self-dressing of the tool electrode during the machining operation. The electrical sparks generated through EDM thermally soften the workpiece as well as expose abrasive particulates from the matrix during machining.

The machining process of EDSG can be controlled either in grinding dominant state with a relatively less contribution of electrical erosion in order to acquire a reduced heat affected surface layer or in an EDM dominant state with a relatively less contribution of grinding to reduce machining force (Kozak, 2002). The balanced state between grinding and the erosion can easily be maintained. The simultaneous spark interactions on the electrode surface leads to self-dressing of tool electrode in the process (Shu and Tu, 2003).

1.13 EDSG process parameters

This section provides a brief overview of the EDSG process parameters and its performance measures.

1.13.1 EDSG input parameters

The electrical and non-electrical control parameters of EDSG, which affects the performance measures are shown in Figure1.20. Out of these control parameters of EDSG some parameters have been selected for the experimental study.

Since, EDSG is a hybrid combination of EDM and grinding processes, the electrical parameters related to EDM have already been discussed in previous section 1.5.1. In the subsequent section non-electrical parameters related to EDSG have been discussed.

1.13.2 Non-electrical parameters of EDSG

The non-electrical parameters can also play a significant role in optimization of performance measures of EDSG process. The various non-electrical parameters of EDSG are discussed as:

a) **Abrasive particle size**: The size of particles in electrodes plays a significant role in the machining of the workpiece. With the increase in size of abrasive particles, the abrasion action becomes considerable and contributes the maximum to material removal rate and minimizing surface roughness.
b) **Abrasive particle concentration**: The quantity of abrasive particles in the matrix also plays a significant role during machining of the workpiece. Electrical and thermal conductivity of the composite tool electrode decreases with an increase in volume of abrasives in the composite. Excessive particulate infiltration can cause inferior results during machining by composite tool electrode.

c) **Rotational Speed**: It is the rotating effect of cylindrical or disc-shaped tool electrode measured in revolution/minute. A centrifugal force effect is generated by rotation of tool electrode that causes more debris to be removed from the machining gap. Appreciable improvement in MRR was achieved due to better flushing and increased grinding action (Yan et al., 2000).

d) **Flushing**: The flushing removes the debris from the machining gap for efficient cutting and improved surface finish of machined material. It also provides fresh dielectric fluid to enter into the machining gap and cools both the tool electrode and workpiece. The past results reveal that flushing pressure affects the surface roughness and the tool wear rate in the process. It also acts as a coolant and plays a significant role in clearing the debris from the machining gap (Kagaya et al., 1986; Wong et al., 1995) (Lonardo and Bruzzone, 1999).
e) **Gain**: Gain is the rate of advancement of the tool towards the workpiece. It is the setting of the machine tool that indicates the sensitivity of servomechanism of the machine tool which in turn ensures the stability of the machining operation (Kansal et al., 2006b).

### 1.13.3 EDSG performance measures

The performance measures used for evaluating the performance of EDSG process are: Material Removal Rate (MRR), Electrode Wear Rate (EWR) and surface roughness (SR). These are discussed as follows:

The MRR is calculated as the weight of material removed from the workpiece over the machining time.

$$MRR \left( \frac{gm}{min.} \right) = \frac{Workpiece \ weight \ loss \ (gm)}{machining \ time \ (min.)} \quad (1)$$

The EWR is calculated by measuring the weight loss from the tool electrode over the machining time.

$$EWR \left( \frac{gm}{min.} \right) = \frac{Tool \ weight \ loss \ (gm)}{machining \ time \ (min.)} \quad (2)$$

The SR of the workpiece can be expressed in the arithmetic average (Ra), average peak to valley height (Rz) of the peak roughness (Rp), etc. It is measured in terms of arithmetic mean (Ra) which is defined as deviation from the mean value.

### 1.14 Composition and properties of AISI D2 die steel

AISI D2 die steel is one of the high carbon steels, alloyed with elements like molybdenum, chromium and vanadium and is widely used for the manufacturing of dies, moulds and cutters due to its exceptional strength and wear resistance properties. This hardened steel has chromium rich alloy carbides in the microstructure. These carbides provide resistance against wear with other metals and abrasive materials. The chemical composition of AISI D2 die steel is shown in Table 1.3.
### Table 1.3: Chemical composition of AISI D2 die steel

<table>
<thead>
<tr>
<th>Elements</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>W</th>
<th>V</th>
<th>Mo</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>1.52</td>
<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
<td>0.1</td>
<td>0.8</td>
<td>12</td>
</tr>
</tbody>
</table>

The mechanical and thermal properties of AISI D2 die steel are depicted in Table 1.4 and 1.5 respectively.

### Table 1.4: Mechanical properties of AISI D2 die steel

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$</td>
<td>7700 kg/m³</td>
</tr>
<tr>
<td>Young’s modulus, $E$</td>
<td>208 GN/m²</td>
</tr>
<tr>
<td>Melting temperature, $T_m$</td>
<td>1984 K</td>
</tr>
<tr>
<td>Reference temperature, $T_o$</td>
<td>298 K</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu$</td>
<td>0.3</td>
</tr>
<tr>
<td>Max. yield strength, $S_{yield}$</td>
<td>3300 MPa</td>
</tr>
<tr>
<td>Latent heat melting, $L_m$</td>
<td>2746 kJ/kg</td>
</tr>
<tr>
<td>Latent heat for evaporation, $L_{ev}$</td>
<td>1586 kJ/kg</td>
</tr>
</tbody>
</table>

### Table 1.5: Thermal properties of AISI D2 die steel

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Thermal conductivity (W/m °C)</th>
<th>Coefficient of thermal expansion (°C)</th>
<th>Specific heat (J/kg/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>298</td>
<td>29</td>
<td>$5.71 \times 10^{-6}$</td>
<td>412.21</td>
</tr>
<tr>
<td>673</td>
<td>29.5</td>
<td>$6.90 \times 10^{-6}$</td>
<td>418.36</td>
</tr>
<tr>
<td>1100</td>
<td>30.7</td>
<td>$10.20 \times 10^{-6}$</td>
<td>421.83</td>
</tr>
<tr>
<td>1990</td>
<td>32.3</td>
<td>$12.00 \times 10^{-6}$</td>
<td>431</td>
</tr>
</tbody>
</table>
1.14.1 Applications of AISI D2 die steel

Figure 1.21 shows the industrial applications of AISI D2 die steel. AISI D2 die steel has numerous applications in manufacturing of blanking, coining, drawing and extrusion dies, burnishing tools, forming rolls, lathe centers, punches, shear blades, slitters, thread rolling, stamping and trimming dies.

Figure 1.21: Industrial applications of AISI D2 die steel (a) Automotive stamping die (b) Tablet punches and dies (c) Shearing blades (d) Progressive stamping die (After web, 2010)

1.15 Metal matrix composites

The term composite refers to the material that is composed up of reinforcement distributed in a continuous phase called matrix. The properties of composites are entirely different from their constituents from which they derived. The properties of the composites depend on the type of reinforcement and its bonding with the metal matrix. The composites can be categorized on the basis of physical or chemical nature of the matrix phase (Surappa, 2003) like ceramic-based composites, metal matrix, carbon-matrix composites and polymer based composites. The commonly used metals for the fabrication of composites are
aluminum and copper. The aluminum based metal matrix composites are having higher strength, improved stiffness, high temperature resistance, improved abrasion and wear resistance properties. These composites can be classified on the basis of the type of reinforcement used e.g., particle-reinforced composites, whisker or fibre based composites, continuous fiber based composites and monofilament based reinforced composites.

1.15.1 Processing routes of aluminum based metal matrix composites (AMCs)
The most commonly used routes for the manufacturing of AMCs are:

(1) **Solid state processing**

   In powder metallurgy route, metal and reinforcement is in powder form and mixed together in required proportion to achieve the desired properties. The compaction of powder is carried out by the hot isostatic press (HIP) or extrusion dies. This processing method is having the advantage of uniform distribution of reinforcement in the metal matrix. The other methods used in solid state processing are diffusion bonding and physical vapour deposition (PVD). Mono filament-reinforced AMCs are manufactured through diffusion bonding route. In PVD the vapour is produced by directing high power electron beam onto the end of a solid bar feed stock (Surappa, 2003).

(2) **Liquid state processing route**

   The liquid state processing includes stir casting, melt infiltration and spray deposition fabrication methods. The stir casting method involves mixing of reinforcement into molten metal with stirring action and allowing the mixture to solidify. Infiltration process and spray deposition are also belonged to the category of liquid state processing. During the infiltration process the liquid metal is injected into the porous pre-form of continuous and short fibres.

   In spray deposition method, feeding of cold metal was made into zone of rapid heat injection to convert into metal spray for deposition. The composites produced from spray deposition are relatively cheaper as compared to stir cast and PM route processing.
1.15.2 Applications of ceramic based MMCs

AMCs are playing their important role in improving the performance, life and economic benefits to the manufacturing industries. The particle reinforced aluminum metal matrix composites (PAMCs) are used as components in aerospace, automobiles, and thermal management. Figure 1.22 shows the industrial applications of MMC. These materials can also be used for the fabrication of valves, suspension system, disk brakes, cylinder liners, connecting rods, crankshaft and gear parts of the automobile. The other applications of PAMCs are bicycles frames and guide vanes for the gas turbine engines.

Figure 1.22: Industrial applications of metal matrix composites (a) Automotive disk brakes (b) Automobile components (c) Sleeves in engine block (d) Connecting rods (After web., 2012)
1.15.3 Composition and properties of 6061Al/Al$_2$O$_3$$_{10\%}$ metal matrix composite

The aluminum alloy (6061 Al) based metal matrix composite has been selected as second candidate material for the study. This composite material has wide applications in defense, aircrafts and automobiles. From this study, the efforts have been made to enhance the machining performance of the composite through EDSG. The chemical composition of 6061Al/Al$_2$O$_3$$_{10\%}$ composite is shown in Table 1.6. The typical properties of Al$_2$O$_3$ particulate based aluminum alloy composite is shown in Table 1.7.

Table 1.6: Chemical composition of 6061 Al/Al$_2$O$_3$$_{10\%}$ composite

<table>
<thead>
<tr>
<th>Material</th>
<th>% Composition in composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stir Cast 6061 Al/Al$_2$O$<em>3$$</em>{10%}$(Composite)</td>
<td>90%</td>
</tr>
<tr>
<td>6061 Al Alloy</td>
<td>90%</td>
</tr>
<tr>
<td>Element</td>
<td>Composition %</td>
</tr>
<tr>
<td>Aluminium</td>
<td>Balance</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.8</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.5</td>
</tr>
<tr>
<td>Iron</td>
<td>0.06</td>
</tr>
<tr>
<td>Copper</td>
<td>0.2</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.005</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.025</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.05</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.05</td>
</tr>
<tr>
<td>Others</td>
<td>0.05</td>
</tr>
<tr>
<td>Al$_2$O$_3$(Particulate)</td>
<td>10%</td>
</tr>
<tr>
<td>Alumina</td>
<td>99.9 % pure</td>
</tr>
<tr>
<td>Mesh Size</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 1.7: Mechanical properties of Al$_2$O$_3$$_{10\%}$ reinforced aluminum alloy composite (Lloyd, 1994)

<table>
<thead>
<tr>
<th>Matrix</th>
<th>Particle (Vol %)</th>
<th>Elastic modulus E (GPa)</th>
<th>Young’s modulus YS (MPa)</th>
<th>Ultimate tensile strength UTS (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014-T6</td>
<td>10</td>
<td>84</td>
<td>483</td>
<td>517</td>
<td>3.3</td>
</tr>
<tr>
<td>2014-T6</td>
<td>15</td>
<td>92</td>
<td>476</td>
<td>503</td>
<td>2.3</td>
</tr>
<tr>
<td>2014-T6</td>
<td>20</td>
<td>101</td>
<td>483</td>
<td>503</td>
<td>1.0</td>
</tr>
<tr>
<td>6061-T6</td>
<td>10</td>
<td>81</td>
<td>296</td>
<td>338</td>
<td>7.5</td>
</tr>
<tr>
<td>6061-T6</td>
<td>15</td>
<td>87</td>
<td>317</td>
<td>359</td>
<td>5.4</td>
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<td>379</td>
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1.16 Scope and organization of the thesis

The thesis comprises both experimental and theoretical components. In the present investigation, the emphasis is to examine the role of combined electrical discharges and mechanical abrasion in improving the performance characteristics of the process. Experiments have been conducted on AISI D2 die steel and 6061 Al/Al₂O₃-10% composite to examine the effect of machining parameters on process performance. The effect of peak current, pulse on-time, pulse off time, rotational speed, abrasive particle size and abrasive particle concentration have been studied to understand the mechanism of material removal and behavior of hybrid energies during the machining process. Later on thermal modeling of EDSG process was carried out to determine the temperature distribution and thermal stresses induced into the workpiece by finite element analysis. The thesis work has been categorized into eight main chapters. Chapter wise brief contents are as follow.

**Chapter 1. Introduction**

This chapter covers the need of non-conventional machining, introduction to advanced machining process, basics of electrical discharge machining. This chapter also highlights the concept of hybrid machining processes with emphasis on electrical discharge surface grinding. The overview of EDSG process and its control parameters is also discussed in this chapter.

**Chapter 2. Literature review**

This chapter contains the literature review highlighting the past developments and findings in electrical discharge machining of AISI D2 die steel and advanced materials. Review on past and latest trends in EDSG has also been discussed. This chapter also highlights the review of available literature on modeling of hybrid machining processes.

**Chapter 3. Problem formulation**

This chapter identifies the research gaps from the available literature and depicts the proposed objectives of the research work.

**Chapter 4. Experimental design and modeling**

This chapter describes the experimental design procedure for design of experiments of AISI D2 die steel and the composite workpiece. Introduction to the Taguchi experimental design approach and basics of finite element modeling have also been discussed in this chapter.
Chapter 5. Experimentation

In this chapter development of experimental set up for EDSG has been discussed. Fabrication procedure for composite tool electrodes and the composite workpiece is included in this chapter. Experimental procedure and plan of conducting the experiments have also been described.

Chapter 6. Results and discussions

Analysis of results obtained after experimentation through Taguchi’s Methodology is described in this chapter. The role of significant parameters during EDSG of both materials has been discussed. The optimal parametric settings for EDSG parameters have been suggested. Surface topography and surface integrity of the machined surface have been discussed in this chapter. The comparison of material removal mechanism of EDSG and EDM for the composite workpiece has been discussed. The confirmation tests conducted for validation of predicted results have also been presented.

Chapter 7. Finite element modeling of EDSG

This chapter includes the description of FEA modeling procedure adopted to develop the thermal model of EDSG process. Effect of various input parameters on temperature and thermal stress distribution has been discussed. Based on modeling (theoretical) results experimental validation results have been presented to validate the thermal model.

Chapter 8. Conclusions and future scope

The conclusions derived from the research work have been listed and the possible scope for extension of research work has been presented in this chapter.

References

The publications and articles referred during review of literature survey and discussion on experimental results have been listed in this section.

Appendix

This section includes conversion charts, derivations and specifications of the equipments used during experimentation.

Publications from the present study

The list of publications published in journals and conferences is presented in this section.