Current research trends in variants of Electrical Discharge Machining: A review

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Abstract

Present manufacturing industries are facing challenges from these advanced materials viz. super alloys, ceramics, and composites, that are hard and difficult to machine, requiring high precision, surface quality which increases machining cost. To meet these challenges, non-conventional machining processes are being employed to achieve higher metal removal rate, better surface finish and greater dimensional accuracy, with less tool wear. Electric Discharge Machining (EDM), a non-conventional process, has a wide applications in automotive, defense, aerospace and micro systems industries plays an excellent role in the development of least cost products with more reliable quality assurance. Die sinking EDM, Rotating pin electrode (RPE), Wire electrical discharge machining (WEDM), Micro- EDM, Dry EDM, Rotary disk electrode electrical discharge machining (RDE-EDM) are some of the variants methods of EDM.

The present paper review the state of the art technology of high-performance machining of advanced materials using Die Sinking EDM, WEDM, Micro-EDM, Dry EDM AND RDE-EDM. The review relies on notable academic publications and recent conference proceedings.

Keywords: *EDM; RDE-EDM, RPE; WEDM, Micro-EDM*

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1. Introduction

The advanced materials have attractive properties i.e., high strength, high bending stiffness, good damping capacity, low thermal expansion, better fatigue characteristics which make them potential material for modern day industrial application. Present manufacturing industries are facing challenges from these advanced materials viz. super alloys, ceramics, and composites, that are hard and difficult to machine, requiring high precision, surface quality which increases machining cost **[1].** To meet these challenges new processes with advanced methodology and tooling needs to be developed. The conventional machining of such advanced materials are often difficult due to the improved thermal, chemical and mechanical properties of new advanced materials. Conventional machining such as turning, milling and drilling etc shows ineffectiveness in machining of advanced materials, since it results in poor materials removal rate, excessive tool wear and increased surface roughness. Non-Conventional Machining processes are classified according to the type of energy used for the machining of the work materials. i.e. Mechanical (Ultrasonic machining(USM), Water jet machining(WJM),Abrasive jet machining (AJM), Thermal Electrical discharge machining(EDM),Electron beam machining(EBM),Laser beam machining(LBM), and Chemical (Chemical machining(CHM),Photo chemical machining(PCM) **[2].** The Electric Discharge Machining (EDM), a thermal material removal process, has firmly established its use in the production of forming tools, dies, molds and effectively machining of advanced materials.

1.1 Overview of EDM

In Electrical Discharge Machining the electrode is moved downward toward the work material until the spark gap (the nearest distance between both electrodes) small enough so that the impressed voltage is great enough to ionize the dielectric **[3].** Short duration discharges (measured in microseconds) are generated in a liquid dielectric gap, which separates tool and work piece. The material in the form of debris is removed with the erosive effect of the electrical discharges from tool and work piece **[4].** EDM does not make direct contact between the electrode and the work piece where it can eliminate mechanical stresses chatter and vibration problems during machining **[5].**

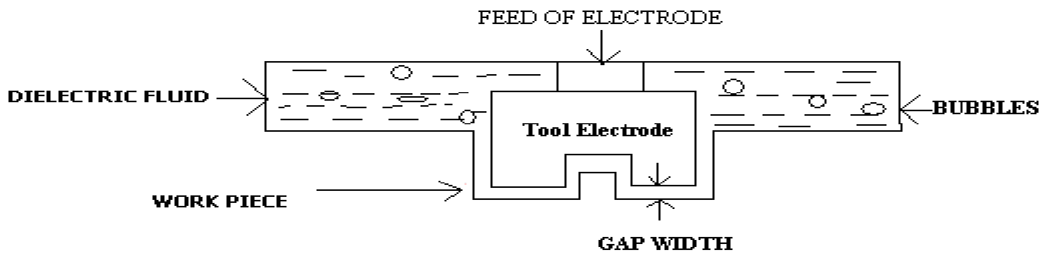

Fig.1.0 Schematic diagram of EDM

EDM is a non-traditional process based on removing unwanted material in the form of debris from a part by means of a series of recurring electrical discharges (created by electric pulse generators in micro seconds) between a tool called electrode and the work material in the presence of a dielectric fluid(kerosene, distilled water) . The history of EDM begins in 1943, with the invention of its principle by Russian scientists Boris and Natalya Lazarenko in Moscow. They were assigned by the Soviet government to investigate the wear caused by sparking between tungsten electrical contacts, a problem which was particularly critical for maintenance of automotive engines during the Second World War. Putting the electrodes in oil, researchers found that the sparks were more uniform and predictable than in air. They had then the idea to reverse the phenomenon, and to use controlled sparking as an erosion method **[6].**Lazarenkos developed during the war the first EDM machines, which were very useful to erode hard metals such as tungsten or tungsten carbide. In the 1950's, progress was made on understanding the erosion phenomenon **[7-9].** It is also during this period that industries produced the first EDM machines. Due to the poor quality of electronic components, the performances of the machines were limited at this time. In the 1960's, the development of the semi-conductor industry permitted considerable improvements in EDM machines. Die-sinking machines became reliable and produced surfaces with controlled quality, whereas wire-cutting machines were still at their very beginning. During the following decades, efforts were principally made in generator design, process automatization, servo-control and robotics. Applications in micro-machining became also of interest during the 1980's **[10].** It is also from this period that the world market of EDM began to increase strongly, and that specific applied EDM research took over basic EDM research **[11].** Finally, new methods for EDM process control arose in the 1990's by using fuzzy control, neural networks response surface methodology, Taguchi optimization.etc.

2. Electrical Discharge Machining (EDM)

This section provides the basic fundamentals of the EDM Process and the variations of process combining other material removal methods:

2.1 EDM: How it works

The material erosion mechanism primarily makes use of electrical energy and turns it into thermal energy through a series of discrete electrical discharges occurring between the electrode and work piece immersed in a dielectric liquid medium **[12].** The thermal energy generates a channel of plasma between the cathode and anode **[13]** at a temperature in the range of 8000 to 12,000 °C **[14].** When the pulsating direct current supply occurring at the rate of approximately 15,000–30,000 Hz **[15]** is turned off, the plasma channel breaks down. This causes a sudden reduction in the temperature allowing the circulating dielectric fluid to implore the plasma channel and flush the molten material from the pole surfaces in the form of microscopic debris.

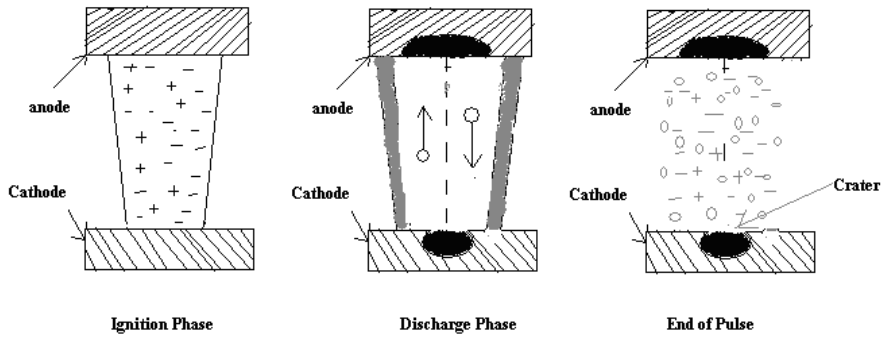

Fig.2.0 The phases of EDM (Konig and klocke, 1997)

Mc Geough **[16]** describes the variation of voltage pulses causing the electrical breakdown of the dielectric fluid. A high voltage current is needed to discharge in order to overcome the dielectric breakdown strength of the small gap. The breakdown of this plasma channel occurs because of the acceleration of electrons towards the anode. Electrons impacts with the neutral atoms and molecule of dielectric fluid, thus creating more positive ions and electrons, which accelerated towards the cathode and anode. The impact of these electrons and positive ions to the anode and cathode produces heat energy.

Electrical Discharge occurs at higher frequencies since the metal removal rate for each discharge is very less in change in weight. For every pulse, electrical discharge occurs at a particular position where the electrode materials are melted and evaporated and finally ejected in the molten phase (in the form of debris) thus forming small crater on both tool electrode and work piece. The unwanted material is then cooled and re-solidified in the dielectric fluid forming large number of debris particles which will be flushed away from the gap by the flow of dielectric pressure. During each end of the discharge duration, the temperature of the plasma channel and the electrode surfaces that is in contact of the plasma rapidly drops, resulting in the recombination of ions and electrons. For maintaining stability in EDM process, every successive next pulse discharge occurs at a spot distanced sufficiently far from the previous discharge position. The pulse interval (known as off time period) for the next discharge pulse should be not so much long and not too short .If it is long then the plasma channel that is generated by the previous discharge can be fully de-ionized and the dielectric breakdown strength around the previous discharge location can be recovered by the time the next voltage charge is applied and short pulse interval time produces more surface roughness and instability in machining **[17].**

2.2 EDM Equipments

Electrical discharge machining unit consist of following components:

2.2.1 EDM Circuits

EDM Circuits helps to convert electrical energy into thermal energy and maintain the machining gap (known as spark gap) to generate succession of uniform electrical discharges in the form of sparks. A capacitor is used in the circuits to store electrical energy before discharging each sparks **[18].**In EDM the most commonly used power supply circuits in EDM process are Resistance –Capacitance (R-C) Circuit, Rotary Impulse Generator Circuit and Controlled Pulse Circuit. RC types of generators are simple and low in cost. It uses resistance and a condenser to generate a nearly a saw tooth voltage waveform. In R-C circuit the condenser of capacitance c is charged through a resistance R_c from a source of current of potential and the charging is continued until the potential of the condenser reaches the breakdown voltage V_c of the gap between the tool and the workpiece.The gap is filled with dielectric fluid. The spark discharge is initiated causing an oscillatory flow of current which reaches a maximum value shortly after the breakdown of the dielectric **[19].** Rotary-impulse generator circuit is simply a motor generator set. This type of generator supplies high voltage in excess of 110v. Arcing is frequent since the voltage waveform is uncontrollable, so the tool wear rate is high. In pulse circuit , vacuum tubes or transistors are used to achieve the pulsing switch effect.Resistence can also be provided in these circuits to slow down the time required for charging the capacitor.

2.2.2 Dielectric Unit:

The dielectric unit systems consist of dielectric tank, a pumping unit and a filtering unit to handle types of dielectric. Dielectric is often used when considering the effect of alternating electric fields on the substance. Mineral oil, kerosene and deionized water are generally used as a dielectric fluid in EDM .The Sinker EDM process uses dielectric acts as a medium through which controlled electrical discharge occours.This dielectric also acts as a quenching medium to cool and solidify the gaseous EDM debris resulting from the discharge **[20].**

2.2.3 Servo feed control:

Servo head is incorporated in EDM to maintain gap voltage since the dielectric parameters constantly fluctuate. Servo mechanism affecting the movement of the electrode may be either electric motor driven, solenoid operated or hydraulically operated or a combination of these. The servo feed control maintain the working gap at proper width **[21].**

2.3 EDM Process Parameters

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

2.3.1 *Electrical Parameters*

- **Pulse Duration (T_{on})**: It is the duration of time measured in micro seconds. During this time period the current is allowed to through the electrode towards the work material within a short gap known as spark gap. Metal removal is directly proportional to the amount of energy applied during the on time period **[22].** Pulse duration is also known as pulse on time and the sparks are generated at certain frequency. Material removal rate depends on longer or shorter pulse on time period. Longer pulse duration improves removal rate of debris from the machined area which also effects on the wear behavior of electrode. As in EDM process erosion takes place in the form of melting and vaporization of both the tool and work material at the same time period, so with longer pulse duration more material has to be melt and vaporize. The resulting crater produced will be broader as comparison to the shorter pulse on time. But, in some experimental research work it has been proved that optimal pulse duration gives higher performance measures **[23].** It conclude all that MRR can not be increased by increasing the Pulse on time, a suitable combination of peak current is also needed for increasing rate of removing unwanted material from the work piece. At constant current and constant duty factor, the MRR is decreased with increase in pulse on time **[24].** This is due to the reason because of short pulses cause less vaporization, where as long pulse duration causes the plasma channel to expand rapidly. This expansion of plasma channel cause less energy density on the work material, which is not sufficient to melt and vaporize the work material. It was also concluded by the researchers that with increase of pulse duration, surface roughness decreased, hardness of work material, crack length, crack width and the thickness of recast layer increased.

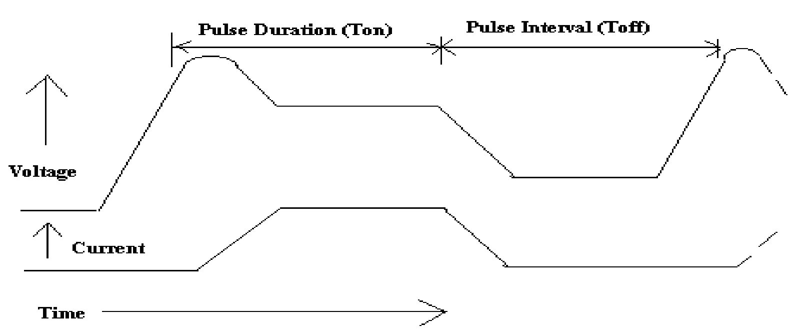

Fig.3.0 Actual profile of single EDM pulse (Fuller, 1996)

- **Pulse Interval (T_{off})**:

It is the waiting interval time period during two pulses on time periods. In fig.1.7, it is the duration of time in which no machining takes place (idle time period) and it allows the melt material to vaporize and to remove from setting. This parameter is to affect the speed and the stability of the cut. If the off-time is too short, it improves MRR but it will because more sparks to be unstable in the machining zone .Kansal et al. **[25]** result out that increase in pulse interval time decreases the MRR. Saha et al. **[26]** reported out that for small value of pulse interval time period, the MRR was low, but with further increase MRR increases. MRR was dropped slowly with increase in pulse interval time. This is due to very short pulse interval the probability of arcing is larger because dielectric in the gap does not recover its dielectric strength. O.A. Abu Zeid investigated the role of voltage, pulse off time in the electro discharge machined AISI T1 high speed steel **[27]**. The researcher concluded that the MRR is not so much sensitive to pulse interval time changes at low pulse on time in finish machining.

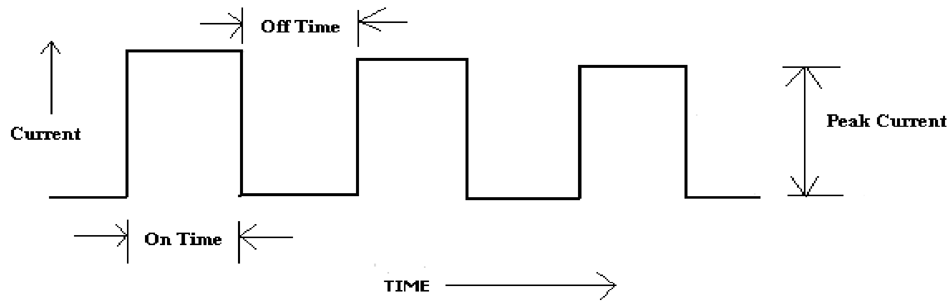

Fig.4.0 Pulse wave form of pulse generator [28]

- **Electrode gap (spark gap):**

It is the distance between the electrode and the part during the process of EDM. An electro-mechanical and hydraulic systems are used to respond to average gap voltage. To obtain good performance and gap stability a suitable gap should be maintained. For the reaction speed, it must obtain a high speed so that it can respond to short circuits or even open gap circuits. Gap width is not measured directly, but can be inferred from the average gap voltage **[28].**

2.3.2 EDM Research

Electrical discharge machining is one of the profitable machining processes used for accurate and high precision geometry of the work piece. EDM can become more reliable by doing the research on performances to be obtained by it. Some of the research areas in EDM are shown in fig.5.0

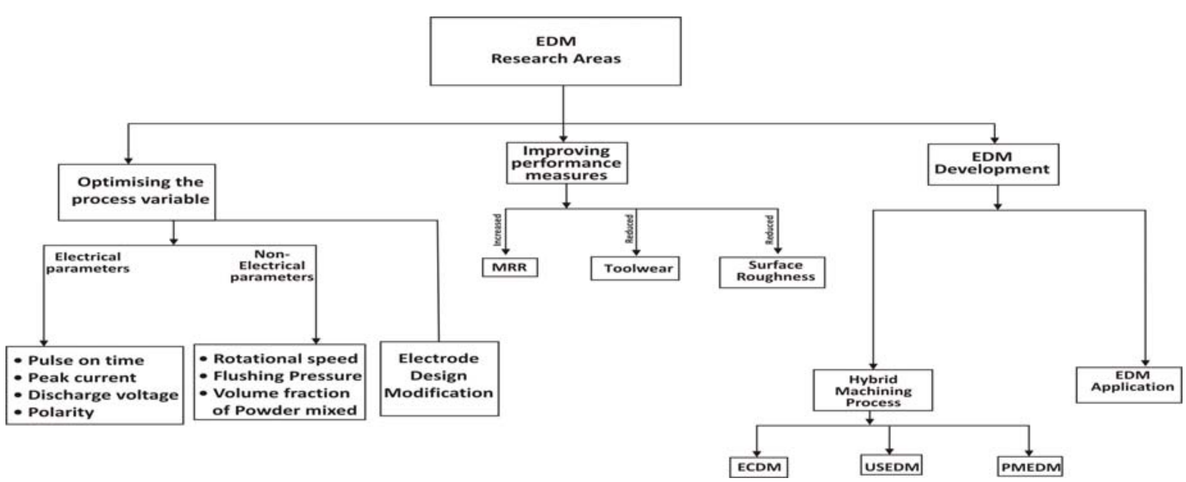

Fig.5.0 Classification of EDM research

- **Duty cycle**:

It is a percentage of the on-time relative to the total cycle time. This parameter is calculated by dividing the on-time by the total cycle time (on-time plus off-time).It indicates the degree of efficiency of the operation.

$$\text{Duty cycle} = \frac{T_{on}}{T_{on} + T_{off}} \qquad \textbf{(1)}$$

F.L.Amarim result out the effect of duty cycle on the machining of AMP-8000. The researchers concluded that increase of duty factor increases MRR. This is due to the reason that with increase of duty cycle a black layer was seen on the surface of work material and with further more increase of it, the machining becomes unstable **[29].**MRR increases with increase in duty factor at constant current constant pulse on time **[24].**This is due to the reason that with increase in duty cycle, the intensity of spark increases resulting in higher MRR.

- **Polarity**:

It may be positive or negative connected to tool electrode or work material. Polarity can affect processing speed, finish, wear and stability of the EDM operation. It has been proved that MRR is more when the tool electrodes are connected at positive polarity(+) than at negative terminal(-) .This may be due to transfer of energy during the charging process is more in this condition of machining. When a electrical discharge is generated electrons dispatch from the negative polarity collides with neutral molecules between the work piece and electrode which is responsible for ionization process in EDM. However, ionization is taken because the electron arrives at the positive terminal of the surface. The negative polarity is more desirable as compared to positive polarity **[30].** The researcher concluded this is because the MRR is higher and better surface finish is produced as MRR is dependent on anode potential drop. Chow et al. experimentally work on the micro slitting on titanium alloy with copper as rotating disk as a electrode. They concluded that MRR was lower with positive polarity of work piece as compared to negative polarity. This is due to the fact that with positive polarity of work piece, the dissociated carbon elements in the dielectric fluid tend to adhere to the anode, which result in forming a recast layer **[31].**

2.4. Non Electrical Parameters

Non-electrical parameters such as the Rotational movement of electrode, flushing of dielectric fluid and aspect ratio (tool shape) together play a significant role in delivering optimal performance measures. This section discusses the effects of non-electrical parameters on the various performance measures.

2.4.1 *Rotation of Tool Electrode:*

It is the rotational effect of cylindrical (pin shaped) or disc shaped electrode tool measured in revolution/minute. The rotational movement of electrode is normal to the work surface and with increasing the speed, a centrifugal force is generated causes more debris to remove faster from the machining zone. According to Mohan et al**. [23]**, the centrifugal force generated throws a layer of dielectric in to the machining gap, induces an atmosphere for better surface finish, prevent arching and improves MRR. Soni and Chakraverti **[32]** compared the various performance measures of rotating electrode with the stationary electrode. The results concluded an improvement in MRR due to the better flushing action and sparking efficiency with little tool wear but the surface finish was improved.

2.4.2 Injection *flushing:*

Flushing removes eroded particles from the gap for efficient cutting and improved surface finish of machined material. Flushing also enables fresh dielectric oil flow into the gap and cools both the electrode and the work piece. Basic characteristics required for dielectric used in EDM are high dielectric strength and quick recovery after breakdown **[33]**.There variations of EDM processes can be classified according to the type of dielectric fluid used. Most dielectric media are hydrocarbon compounds and water. The hydrocarbon compounds are in the form of refined oil; better known as kerosene. While the fluid properties are essential, the correct fluid circulating methodology is also important. The dielectric fluid not only forms a dielectric barrier for the spark between the work piece and the electrode but also cools the eroded particles between the work piece and the electrode. The pressurized fluid flushes out the eroded gap particles and remove the debris from the fluid medium by causing the fluid to pass through a filter system **[34].**During the investigation of EDM of Ti 6Al 4V, Chen et al. **[35]** found that the MRR was greater and the relative EWR is lower, when using 16 distilled water as dielectric solution.

2.4.3 *Tool Geometry:*

Tool geometry is concerned with the shape of the tool electrodes.ie. Square, rectangle, cylindrical, circular.etc. The ratio of length /diameter of any shaped feature of material. In case of rotating disk electrode the ratio becomes thickness/diameter. Murali et al **[36**] used graphite foil for straight grooving operation instead of pin shaped electrode. An aspect ratio of 2.3 was achieved by using FAST technique (Foil as tool electrode) which was improved to 8 by implementing GAME (Gravity assisted Micro EDM). Singh et al**. [37]** uses square and rectangular shaped electrodes having aspect ratio of 1.0 and 0.6 for machining $6061Al/Al_2O_{3P}$ composite .It concluded that shape of the electrode effects EWR. The tool having less aspect ratio gave higher value of EWR.Thus with increasing the size of electrode more good performance of ED Machining takes place.

2.4.4 Tool *Material (Electrode):*

Engineering materials having higher thermal conductivity and melting point are used as a tool material for EDM process of machining . Copper, graphite, copper-tungsten, silver tungsten, copper graphite and brass are used as a tool material (electrode) in EDM. They all have good wear characteristics, better conductivity, and better sparking conditions for machining. Copper with 5% tellurium, added for better machining properties. Tungsten resist wear better than copper and brass .Brass ensures stable sparking conditions and is normally used for specialized applications such as drilling of small holes where the high electrode wear is acceptable (Metals Handbook, 1989). The factors that effect selection of electrode material include metal removal rate, wear resistance, desired surface finish, cost of electrode material manufacture and material and characteristics of work material to be machined.

2.5 Recast Layer in EDM:

In EDM process as the sparks are generated the material begins to melt and vaporize with small crater, thus reducing the area of work piece material into gas bubbles. During the each cycle period EDMed crater gets larger, its increasing surface area begins to sink heat away from the spark gap until the vaporization temperature can no longer be sustained. The melting process continue but an pulse interval time period is required to flush away the eroded material .During the off time period when the current is switched off, melting ceases instantly and all molten material break away in the form of small spherical bubbles is drawn back by the surface tension and resolidifies back on to the cooler layer of cut material. This thin layer of resolidified material is called recast layer or white layer **[38].** Immediately below the recast layer is the area termed as heat affected zone (HAZ). This area is partially affected by the elevated temperature of the spark gap. Within this area, the material did not approach temperature large to melt, but reaches a temperature high to change its temper, reducing its hardness. While machining the maraging steel with EDM process a recast layer was formed **[24].** These results in premature part failure and shorten the life of part's fine surface finish.

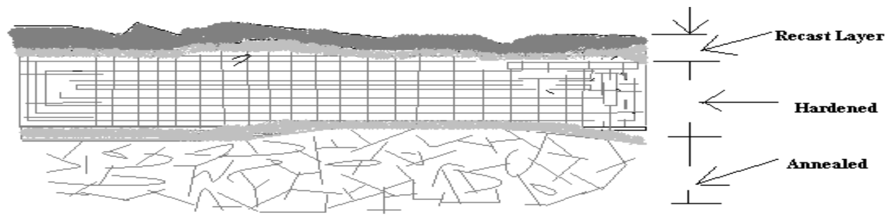

Fig.6.0 EDM heat effected Zones [41]

Pandey et al. **[39]** reported out that the thickness of the recast layer formed on the work piece and the level of thermal damage suffered by the electrode can be determined by analyzing the growth of the plasma channel during sparking. The EDM generates heat affected zone in the machining zone **[40]**. The researchers measured the micro hardness around the micro- EDMed hole crossections. They concluded that HAZ in micro EDM comprises of low hardness instead of white layer.

3.0 EDM Variants

In die sinking process the tool electrode is the replica of the machined profile of the work material shown in fig 7.0 Die sinking process solves the problem of manufacturing accurate and complex-shaped electrodes of three-dimensional cavities. According to the article "Advancing EDM through Fundamental Insight into the Process" by M. Kunieda Tokyo University of Agriculture and Technology, Japan), B. Lauwers (Katholieke Universities Leuven, Belgium), K.P. Rajukar (University of Nebraska-Lincoln, USA), B.M Schumacher (University of Applied Science St Gallen, Switzerland),the work piece can be formed either by replication of a shaped tool electrode or by 3-Dimensional movement of a simple electrode similar to milling or we can use the combination of both the methods.

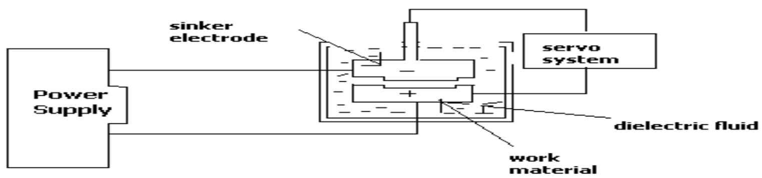

Fig.7.0 Schematic diagram of Die-sinking EDM

A number of EDM variations based on this basic configuration have emerged in the industry to cope with the machining of smart materials or super alloys used exclusively in the manufacture of aeronautical and aerospace parts. Wire-cut EDM (WEDM) and Rotary Disk electrode electrical discharge machining process (RDE-EDM) are some of the most favorable variants owing to its ability to machine conductive, exotic and high strength and temperature resistive (HSTR) materials with the scope of generating intricate shapes and profiles **[41].**

3.1 Wire EDM process:

WEDM was first introduced to the manufacturing industry in the late 1960s. In WEDM, material is eroded from the work material by a series of discrete sparks occurring between the work piece and the wire separated by a stream of dielectric fluid, which is continuously fed to the machining zone **[42].** The WEDM process makes use of electrical energy generating a channel of plasma between the cathode and anode **[43],** and turns it into thermal energy at a temperature in the range of 8000–12,000 ºC **[44]**. When the pulsating direct current power supply occurring between 20,000 and 30,000 Hz **[45]** is turned off, the plasma channel breaks down. This causes a sudden reduction in the temperature allowing the circulating dielectric fluid to implore the plasma channel and flush the molten particles from the pole surfaces in the form of microscopic debris.

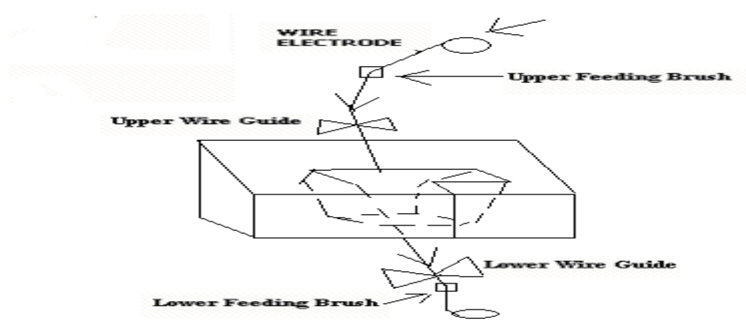

Fig.8.0 Schematic diagram of Wire EDM process [2]

3.1.1 *WEDM process monitoring and control of smart material*

Lok et al. **[46]** presented the finding of processing two advanced materials Sialon and Al_2O_3-TiC by using WEDM. The author has taken MRR and surface finish as output parameters. The surface damage was evaluated by flexural strength data. The variability of flexural strength data was analyzed by weibull stastical method. The mean flexural strength drops from 32% to 67% due to thermal spalling erosion mechanism of wire-cut EDM process. Yan et al**. [47]** machined aluminum matrix composites (Al_2O_3p/6061 Al) using WEDM. The effect of pulse on time, cutting speed, width of slit, surface roughness was studied. The wire easily got broken while machining Al_2O_3p/6061 Al. It was observed that that the cutting speed, surface roughness and width of the slit significantly depend upon volume fraction of Al_2O_3 particles. Less volume percentage of reinforcement increases the surface finish, improves width of slit.

Hascaly et al**. [48]** performed an experiment for finding out the machining characteristics of AISI D5 tool steel in WEDM. The author concluded that intensity of process energy affect the surface roughness as well as micro cracking. The wire speed and fluid pressure do not have much influence. Gokler et al**. [49]** performed experiments to optimize the cutting and offset parameter combination for WEDM process to achieve the desired surface roughness. The author has performed experiments on 1040 steel material of thickness 30, 60 and 80 mm and on 2379 and 2378 steel materials of thickness 30 and 60 mm. It was concluded that increase in the work piece thickness creates better surface roughness characteristic.Tarng et al**. [50]** used a neural network system to determine settings of pulse duration, pulse interval, peak current, open circuit voltage, servo reference voltage, electric capacitance, and table speed for the estimation of cutting speed and surface finish.

3.1.2 *Wire breakage in EDM*

A wide variety of the control strategies preventing the wire from breaking are built on the knowledge of the characteristics of wire breakage .Saha et al**. [51]** developed a model that predicts the thermal distribution accurately, increase wire velocity and reduction in heat transfer coefficient. He has found that non uniform heating is the most important variable affecting the temperature stress. FE Model would help to prevent wire breakage. Tosun et al. **[52]** found that increasing pulse duration and open circuit voltage increase the wire wear rate, whereas the increasing wire speed and dielectric fluid pressure decreases the wire wear. Luo et al. **[53]** claimed that the wire material yielding and fracture contribute to the wire breakage, whilst an increase in temperature aggravates the failure process.

3.1.3 *Modeling of WEDM process*

Tarng et al. **[50]** formulated a neural network model and simulated annealing algorithm in order to predict and optimize the surface roughness and cutting velocity of the WEDM process when machining of SUS-304 stainless steel materials. T.A. Spedding and Z.Q.Wang **[54]** attempted to model the cutting speed and surface roughness of WEDM process through the response-surface methodology and artificial neural networks (ANNs) and have found that the model accuracy of both the approaches were better. The same authors (T.A. Spedding and Z.G. Wang, 1997) attempted further to optimize the surface roughness, surface waviness and speed of the artificial neural networks that predicted values using a constrained optimization model. Lin et al. **[55]** proposed a control strategy based on fuzzy logic to improve the machining accuracy. Huang and Liao **[56]** presented the use of Grey relational and S/N ratio analyses, for determining the optimal parameters setting of WEDM process. The results showed that the MRR and surface roughness are easily influenced by the table feed rate and pulse on time.

3.2 MICRO EDM

According to CIRP committee of Physical and Chemical processes, the term micro-machining defines the processes that manufacture products in the range of 1 to 999 μm **[57].** Initially, the term was used to present the miniaturization of electronic components and devices. However, with the present trend in the miniaturization of mechanical components, it is also being applied for the generation of microscopic mechanical components and devices**[28].**In order to reduce the size of product micro-edm was developed and the basic physical characteristics of the micro-EDM process is essentially similar to that of the conventional EDM process with the main difference being in the size of the tool(electrode) used, the power supply of current and voltage supply , and the resolution of the X-, Y- and Z- axes movement. The system has a servo system with highest sensitivity and positional accuracy of $\pm$ 0.5 µm **[58]**.It permits setting of a minimized discharge gap width of 1 µm **[59].** There fore, the system is helpful for conventional precision engineering purposes as well as for micro-components fabrication like micro-molds, micro inserts, and in general filigree structure up to 5 µm **[58].**

Yan et al. **[60]** investigated effects of various machining parameters on the quality of the micro-hole machining of carbide by EDM. Fuel injector valves, parts and components for medical devices, fiber optic connectors, micromachining, micro-mold making, stamping tools, and micro electronic parts are the examples of miniaturized and smaller size parts produced by the micro-EDM technology. . Zhang et al. **[61]** made an experiment in hole machining of Al_2O_3 ceramics with small diameter and metal bond diamond wheels after micro electric discharge truing to investigate its effectiveness.

Wansheng et al. **[62]** demonstrated that holes with diameter less than 0.2 mm and the aspect ratio more than 15 can be produced without difficulty by ultrasonic vibration using micro-EDM .Kaminski and Capuano **[63]** reported that they studied parameters affecting the micro-hole machining process with diameters smaller than 0.1 mm and aspect ratio bigger than 20 by electro erosion penetration process in sheets. Diver et al. **[64]** investigated the possibility of a novel technique to produce reverse tapered micro-holes using EDM. High quality reverse tapered holes are claimed to be produced, showing excellent hole form, with hole diameter variation around 3 µm and cycle times similar to standard EDM for straight holes. The quality of hole surface finish maintained at Ra=0.3 µm. Liu et al**. [65]** investigated the feasibility of fabricating high nickel alloy using micro-EDM, and micro-holes were successfully fabricated in high nickel alloy. Liu et al**. [66]** studied micro-EDM combined with High-Frequency Dither Grinding (HFDG) to improve the surface roughness of micro-holes, reducing from 2.12 µm to 0.85 µm without micro cracks.

3.3 DRY EDM:

Dry EDM uses gas-liquid mixture as the two phase dielectric fluid and has the advantage the concentration of liquid and properties of dielectric fluid to meet desired performance responses. In dry EDM, tool electrode is formed to be thin walled pipe. Dry EDM uses gas as dielectric fluid, and high MRR can be obtained to cut high strength engineering materials with the presence of oxygen **[67–70]**.High-pressure gas or air is supplied through the pipe. The role of the gas is to remove the debris from the gap and to cool the inter electrode gap. The technique was developed to decrease the pollution caused by the use of liquid dielectric which leads to production of vapour during machining and the cost to manage the waste. V.Ramani et al. **[71]** reported that helium and argon can be used as a dielectric medium to drill holes using copper electrodes. Later on Kunieda et al. **[72]** confirm that by introducing oxygen gas into the discharge gap increases the material removal rate in water as a dielectric medium. Tao et al. **[73]** concluded that by combining oxygen gas with copper tool gives high MRR in dry EDM. Dry EDM with air as the dielectric is feasible with reverse polarity **[26]**.

3.4 Rotating Disk Electrode(RDE)-EDM:

Machining by using Rotary Disk Electrode is a typical method of EDM, which develops in recent years. In recent years the studying of micro electro mechanical Systems (MEMS) have resulted in the manufacture of small size products such as micro-pumps, micro-engines and micro-robots that have been successfully used in industrial applications. The technique of precision machining for such small devices has become increasingly important **[74–77].** Rotary disc electrode electrical discharge machining is one of the variant process of electrical discharge machining process based on removing unwanted material in the form of debris from a part by means of a series of recurring electrical discharges (created by electric pulse generators in micro seconds)between a rotary tool called disc(thickness ranging from micron level to 1 mm) and the work material in the presence of a dielectric fluid(kerosene, distilled water). This fluid makes it possible to flush eroded particles from the gap.

This new application of RDE-EDM machining is achieved by locating the rotating disk Electrode above or below the work piece to improve the debris removal rate.

3.4.1 Past work done on RDE-EDM:

A significant number of papers have been reviewed on ways of yielding optimal performance measures of high MRR, low tool wear rate (TWR) and satisfactory surface quality. This section will review all the past research work done in rotary EDM for machining advanced materials.

Several researchers have explained the material removal mechanism in terms of migration of material elements between the rotary disk electrode (RDE) and work piece. The material removal takes place not only by vapour ejection but also due to liquid expulsion. Sato et al. **[78]** developed an electrical discharge machine for micro-hole boring. They claimed that electrode rotation served as an effective gap flushing technique, yielding better material removal.

Soni & Chakraverti **[32]** introduced rotary disc for grooving operation on titanium alloy. The rotary electrode was placed above the work material. The difficulty of debris problem was encountered the research work i.e. lower metal removal rate and arching occurs due to the accumulation of debris particle between the electrode and work piece.

Soni et al. **[79]** experimented the machining of die steel and titanium alloy with a rotary and low vibrating copper-tungsten electrode revealed that electrode rotation improves the material removal rate. They also studied the alloying effect of migrating material from electrode and work material. During the research it was observed that performance measures between rotary and stationary electrodes revealed improvement in material removal due to better flushing action and sparking efficiency with low electrode wear during rotary electrical discharge machining. Soni et al. **[80]** uses copper-tungsten electrode for blind and through hole operation on high carbon high chromium die steel and titanium alloy. It was found that metal removal rate was increased due to rotating electrode which increases the flushing action. Material removal rate was more in case of die steel than titanium allow due to its lower specific strength and less hardness.

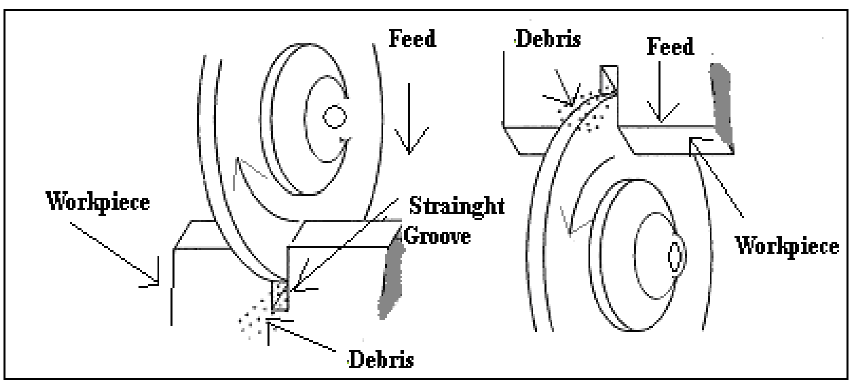

Fig.9.0 Rotating Disk Electrode Schematic Diagram [81]

Chow et al**. [81]** used rotary electrode in a modified conventional electrical discharge machine for micro slitting of work piece. The research concluded that increase in material removal and uniform decrease in electrode wear around its periphery by locating the work piece above rotary disk electrode. Reduction in recast layer thickness and lesser micro cracks concentration was also observed on the eroded surface. Yan et al**. [82**] optimized the cutting of Al_2O_3/6061Al composite using rotary electrical discharge machining with a disk like electrode with Taguchi methodology. Taguchi methodology revealed that, in general electrical parameters (Peak Current, Pulse duration and gap voltage) affects the machining characteristics(material removal rate, electrode wear rate & surface roughness) more significantly than the non-electrical parameters (speed of rotational disc).High MRR was found due to superior debris disposal effect of RDE.

C.C.Wang et al. **[83]** optimizes the blind-hole drilling of Al_2O_3/6061Al composite using rotary electro-discharging machining by using Taguchi methodology. Increase of rotational speed of the electrode or the injection flushing pressure of the dielectric fluid result in a higher MRR. Ghoreishi and Atkinson **[84]** compared the effects of high and low frequency forced axial vibration of the electrode rotation in EDM. Vibro-rotary increases less material removal rate as compared with vibration EDM alone but improved surface finish .Combination of ultrasonic vibration and rotation of electrode leads to increase in MRR, TWR AND SR. Mohan et al. **[85]** studied the effect of machining variables on MRR.EWR AND SR by blind hole drilling through cylindrical rotary electrode (copper) and compared its result from stationary electrode .MRR increases with increase in discharge current and for specific current it decreases with increases in pulse duration. MRR decreases with increase in vol. % of Sic but Increases with rotational speed of electrode which results in positive effect with MRR, TWR and better SR than stationary electrode. Mohan et al. **[23]** studied the effect of machining variables by blind hole drilling through cylindrical tube electrode made of brass, having eccentric hole diameters .MRR increases with increase of discharge currents and MRR, EWR and SR were more with positive polarity of the electrode than at negative.

M.Murali et al. **[36]** uses a graphite foil for making straight grooves by Foil as tool electrode approach (FAST).The profile made by FAST EDM appears to have a concave shape with raised edges. This was further refined by using the Gravitational assisted micro EDM (GAME) in which work material was placed above the foil electrode for the effective debris removal, which has improved the aspect ratio to about 8.

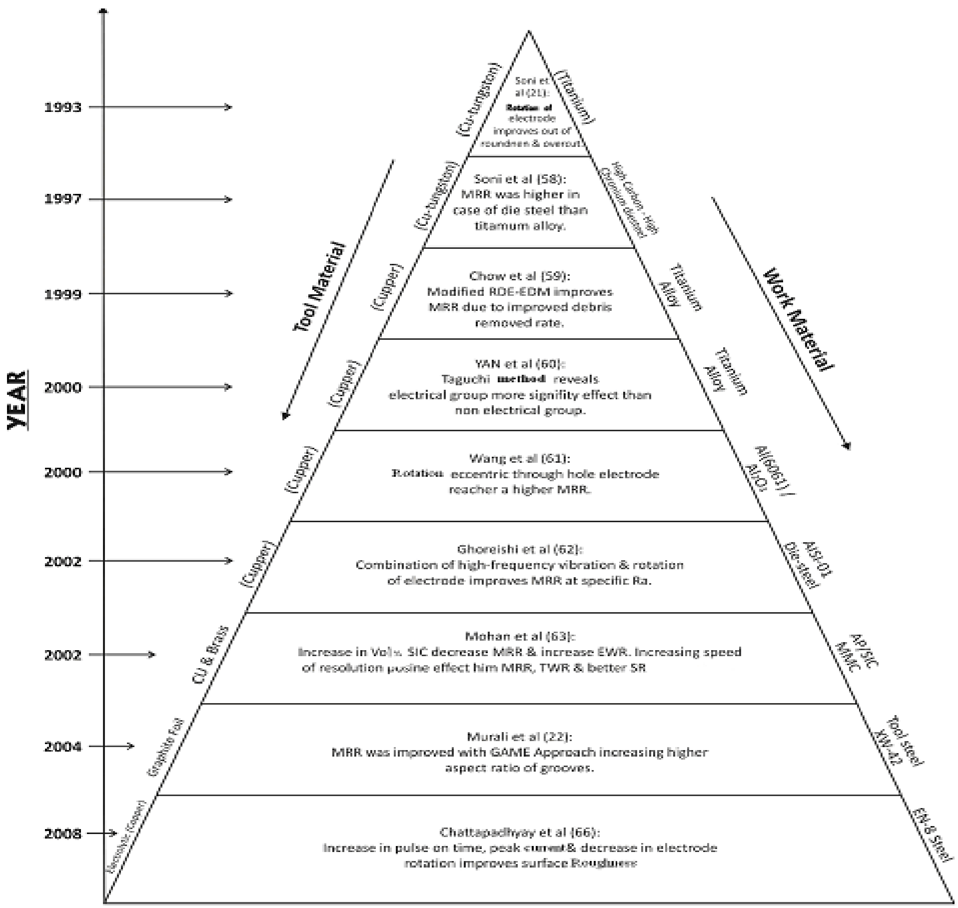

Fig.10. Rotary EDM performance

Kuo et al. **[86]** fabricated the micro disk by the application of micro EDM through Wire. The series-pattern micro-disk was used as a rotating tool electrode, which is referred to as micro-rotating disk electrode (MRDE), to simultaneously achieve micro-slits with widths as low as 8 µm. Shih et al. **[87]** have reported about the electrical discharge grinding of AISI D2 tool steel work piece using a rotary disk copper electrode mounted on horizontal spindle. It was observed that lower electrode wear rate and higher material removal rate can be obtained in this process. Chattopadhyay et al. **[88]** investigates the machining characteristics of EN-8 steel with copper as a tool electrode during rotary electrical discharge machining process. In the case of MRR and EWR, it has been seen that the decrease in pulse on time, decrease in electrode rotation and increase in peak current, increases both the machining output, while investigation is carried out with rotary electrode.

4.0 Hybrid Electrical Discharge Machining Processes

Hybrid machining process in EDM make use of the combined advantages and to reduce some negative effects the combined processes produce better performance as compared to individual process machining. In EDM process the electrical energy is converted to thermal energy, the combined effect of powder suspension and ultrasonic motion of tool or work piece as been reported in this section.

4.1 Powder mixed EDM (PMEDM)

EDM process in pure kerosene shows instability resulting to the arcing effect. In order to improve the machining efficiency, the addition of abrasives and metallic powders is done to dielectric fluid. Erden et al**. [89]** research out the effect of suspended powder particles (Al, Cu, Fe, and carbon) on the mach inability of mild steel. It was observed that the added powder increases the breakdown characteristics of the dielectric fluid, and the machining rate increases with an increase in the concentration of the added powder. It was also observed that the machining becomes Unstable and difficult at an excessive powder concentration due to the occurrence of short-circuiting. Jeswani et al. **[90]** carried out the research by the addition of fine graphite powder into kerosene oil on the machining of tool steels. It was resulted out that the addition of 4 g/l of graphite powder increases the interspace for electric discharge initiation and lowered the breakdown voltage.

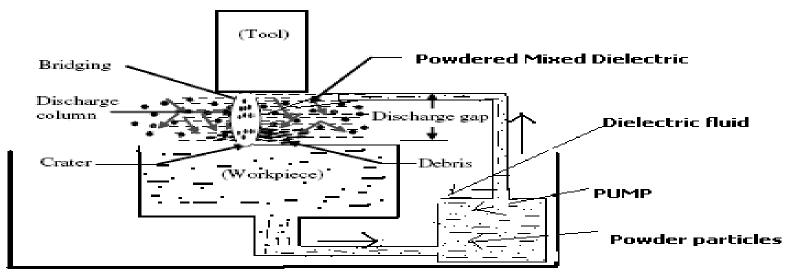

Fig.11.0 Schematic diagram of PMEDM

Narumiya et al**. [91]** studied the addition aluminum and graphite powders in dielectric fluid which results in better surface finish than the silicon powder. The best results are obtained for aluminum and graphite powder particles having diameters less than 15 μm and concentration ranges from 2 to 15 g/l. Mohri et al. **[92]** studied the effect of silicon powder addition into dielectric fluid on the surface finish of H-13 die steel. Machining with addition of silicon powder produces fine and corrosion-resistant surfaces having roughness of 2 μm. Kobayashi et al**. [93]** investigated the effects of suspended powder in dielectric fluid on surface roughness. It was reported that the surface finish of SKD-61 material is improved with the use of silicon powder. Yan et al. **[94]** studied the effect of suspended aluminum and silicon carbide powders on EDM of SKD11 and Ti-6Al-4V. Improvement in metal removal rate was observed at the cost of surface finish.

Ming et al. **[95]** studied out the additives (conductive and inorganic oxide particles) increases the Metal removal rate and decreases the tool wear rate, and improves the surface quality of the work material. Uno et al. **[96]** investigated the effect of silicon powder mixing on the surface generation mechanism. The EDM with silicon powder mixed fluid produced better surface finish as compared to those produced by EDM with kerosene fluid. It was argued that silicon powder mixed EDM fluid led to smaller undulation of a crater because the impact force acting on the work piece is smaller. This results in the stable machining without a short-circuit between the electrode and the work material. In another study, Uno et al. **[97]** result out that nickel powder mixed EDM modifies the surface of aluminum bronze components. Nickel powder deposit a layer on an EDM surface to make the surface abrasion-resistant. Wong et al. **[98]** observed that machining of SKH-54 tool steel in addition of graphite powder particles results in higher material removal rate and better discharge dispersion. Chow et al. **[99]** studied the EDM process by adding Sic and aluminum powders into kerosene for the micro- slit machining of titanium alloy. Mixed Sic and aluminum powder to the kerosene enhanced the gap distance, resulting in higher debris removal rate and material removal depth. Pecas et al. **[100]** result out the effect of silicon powder mixed dielectric on EDM. Improvement in surface finish was assessed through quality surface indicators and process time measurements over a set of different processing areas.

Kansal et al. **[101]** experimentally studied the effect of addition of silicon powder in dielectric fluid and enhanced rate of material removal and surface finish was achieved. Empirical modelling with response surface methodology concluded the variation of response parameters in terms of independent parameters within the specified range. The silicon powder suspended in the dielectric fluid of EDM affects both MRR and SR. It was found that MRR increases with the increase in the concentration of the silicon powder. Later on Kansal et al. **[25]** studied the effect of addition of silicon powder on machining rate of AISI D2 Die Steel. It was found that Peak current, concentration of the silicon powder; pulse-on time, pulse-off time, and gain significantly affect the material removal rate in PMEDM. Chow et al. **[102]** uses Sic powder in water as dielectric for micro slit operation. They concluded that the addition of Sic powder increases the electrical conductivity, enlarge the inter electrode gap, removes debris easily and increases MRR.Till very few researches has been seen in grooving and slitting machining operation with addition of powder mixed EDM. Kozak et al. **[103]** have estimated that electrical breakdown in the gap with conducting/non-conducting abrasive powders would be initiated at 3 or 1.5 times larger distance than in case of EDM with pure dielectric fluid, respectively. Extensive studies on the role of abrasives in AEDM have revealed that in hybrid ED process, using abrasive powder, the thermal erosion phenomenon is directly involved in metal removal whereas, the presence of powder assists in improving the machining capabilities by creating a favourable machining environment. Some hybrid processes have also been employed on composites to study their effects. Abrasive powder-mixed EDM or Abrasive EDM (AEDM) was utilised to explore the influences of process parameters. This process requires proper powder suspension and continuous filtration for ensuring even distribution throughout the cavity, facilitating excellent sidewall finishes, thus restricting it to finish machining of component **[104].**

Later on a comparative machinability study has also been carried out on stir-casted 6061Al/Al_2O_3p/20p work specimens with copper electrode tools by using plain dielectric fluid and Silicon Carbide (Sic) abrasive powder-suspended dielectric fluid and evaluating the machinability in terms of Surface Roughness (SR). The results of both the processes were analysed using Lenth's method to find the significant parameters and obtaining optimum machining parameter settings. It was found experimentally that Abrasive Particle Size (APS); Abrasive Particle Concentration (APC) and pulse current are the most significant parameters that affect the surface characteristics**[105].** Singh et al. analyse the effect of Abrasive powder-mixed EDM of 6061Al/Al2O3p/20p work specimens with copper tool electrode .They concluded that tool electrode lift time and aspect ratio (shape of the tool electrode) also have considerable effect on the machining performance. Experimental results also indicate that compared with conventional EDM, APM/EDM performance, as regards metal removal rate and surface finish, is much superior. In this study, the MRR in APM/EDM is almost twice that possible with EDM. Similar trend is also noticed for surface finish **[106].**

4.2 Ultrasonic Assisted EDM (USEDM)

The hybrid effect ultrasonic vibration of the electrode with EDM has been undertaken since mid 1980s. Ultrasonic is concerned with the vibratory wave of frequency above 16 Kc/s **[107].** Ultrasonic machining combined with Electrical discharge machining can improve material removal rate as high as possible on account of decreasing surface finish. It can be used to machine high strength materials i.e. composites and super alloys. In USEDM process the abrasive slurry is replaced by suitable dielectric fluid (kerosene, distilled water,). The Ultrasonic vibration of tool or work piece in combination with electrical discharges produced by the electrode removes material effectively. The motion of direction of tool is generally normal to the work surface. The vibrating movement of the tool electrode or the work piece improves the slurry circulation and the pumping action, by pushing the debris away and sucking new fresh dielectric and which provides ideal condition for discharges, their efficiency and gives higher removal rate **[108].**

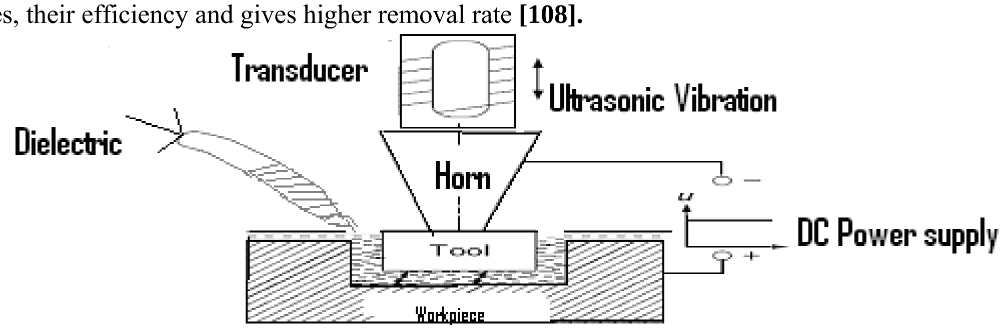

Fig.12.0 Schematic diagram of USEDM [2]

4.2.1 *Tool Vibration in EDM*

Murti and Philip **(109)** added that with the combination of ultrasonic vibration in EDM the MRR and surface finish improved significantly and the tool wear rate increased. Zhixin et al**. [110]** has produced an ultrasonic vibration pulse electro-discharge machining (UVPEDM) to produce holes in ceramics material. High material removal rate (MRR) was confirmed during the experimental work. Ogawa et al. [**111]** reported out that the depth of micro holes by the combined effect of EDM with ultrasonic vibration becomes almost two times as that without ultrasonic vibration and machining rate was increased. Yan et al. **[112]** result out that with combined effect of micro electrical discharge machining (MEDM) and micro ultrasonic vibration machining (MUSM) , the diameter variation between the entrance and exit (DVEE) could obtained about 2 mm in micro holes with diameters of about 150 mm and depth of 500 mm. Ghoreishi and Atkinson **[81]** compared the effects of high and low frequency forced axial vibration of the electrode, rotation of the electrode and combinations of the methods in respect of MRR, tool wear ratio (TWR) and surface quality in EDM die sinking process. They concluded that vibro-rotary increases MRR by up to 35% compared with vibration EDM and by up to 100% compared with rotary EDM in semi finishing.

4.2.2 *Work piece Vibration in EDM*

Egashira et al.**[113]** adopted to vibrate the work piece during machining. Micro holes as small as 5 m in diameter in quartz glass and silicon was machined by EDM with combined effect vibration. In the machining range, high tool wear occurs and sintered diamond tool was used to make machining effective. Prihandana et al. **[114**] work out the effect of vibratory work piece. It was result out that work piece vibration increases the flushing effect and high amplitude combined with high frequency increase the MRR. Till less research work has been reported with work piece vibratory motion by EDM process.

5.0 Summary

EDM has resulted out as most cost effective and precision machining process in recent years. The capacity of machining hard and difficult to machine parts has made EDM as one of the most important machining processes. The contribution Variants of EDM has brought tremendous improvements in the surface finish of machined advanced engineering materials. Powder mixed EDM and Ultrasonic assisted EDM has not only reduces tool wear but also increases material removal rate. Modeling and optimization of various electrical and non electrical parameters in EDM improved in precision machining of work materials The review of the research trends in EDM on rotary EDM, dry EDM machining, EDM with powder additives, Ultrasonic assisted EDM ,WEDM and Micro EDM performances is presented. In each topic, the development of the methods for the last 50 years is discussed.

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