International Journal of Research in Advent Technology, Vol.2, No.3, March 2014
E-ISSN: 2321-9637

Current Advanced Research Development of Electric Discharge Machining (EDM): A Review

Sushil Kumar Choudhary [1]
(Research Scholar)
&
Dr. R.S Jadoun[2]
(Professor)
Department[1,2] of Industrial & Production Engineering, G.B.Pant University of Agriculture & Technology, Pantnagar, Uttarakhand, India.
(Sushil_think@rediffmail.com)[1]

Abstract -Electrical discharge machining (EDM) process is one of the most commonly used non-conventional precise material removal processes. Electrical discharge machining (EDM) is a process for shaping hard metals and forming deep complex shaped holes by arc erosion in all kinds of electro-conductive materials. Erosion pulse discharge occurs in a small gap between the work piece and the electrode. This removes the unwanted material from the parent metal through melting and vaporizing in presence of dielectric fluid. In recent years, EDM researchers have explored a number of ways to improve EDM Process parameters such as Electrical parameters, Non-Electrical Parameters, tool Electrode based parameters & Powder based parameters. This new research shares the same objectives of achieving more efficient metal removal rate reduction in tool wear and improved surface quality. This paper reviews the research work carried out from the inception to the development of die-sinking EDM, Water in EDM, dry EDM, and Powder mixed electric Discharge Machining. Within the past decade. & also briefly describing the Current Research technique Trend in EDM, future EDM research direction.

Key Word-Electrical Discharge Machining (EDM), Dry EDM, PMEDM, MRR, TWR, SQ

I INTRODUCTION OF EDM

Electrical Discharge Machining (EDM) is non traditional, no physical cutting forces between the tool and the workpiece, high precision metal removal process using thermal energy by generating a spark to erode the workpiece. The workpiece must be a conductive electricity material which is submerged into the dielectric fluid for better erosion. EDM machine has wide application in production of die cavity with large components, deep small diameter whole and various intricate holes and other precision part.

. The history of EDM Machining Techniques goes as far back as 1770, when English chemist Joseph Priestly discovered the erosive effect of electrical discharges or sparks. The EDM process was invented by two Russian scientists, Dr. B.R. Lazarenko and Dr. N.I. Lazarenko in 1943. The spark generator used in 1943, known as the Lazarenko circuit, has been employed over many years in power supplies for EDM machines and proved to be used in many current applications. The Lazarenko EDM system uses resistance-capacitance type of power supply, which was widely used at the EDM machine in the 1950's and later served as the model for successive development in EDM. Further developments in the 1960's of pulse and solid state generators reduced previous problems with weak electrode as well as the inventions of orbiting systems. In the 1970's the number of electrodes is reduced to create cavities. Finally, in the 1980's a computer numerical controlled (CNC) EDM was introduced in USA.

The new concept of manufacturing uses non-conventional energy sources like sound, light, mechanical, chemical, electrical, electrons and ions. With the industrial and technological growth, development of harder and difficult to machine materials, which find wide application in aerospace, nuclear engineering and other industries owing to their high strength to weight ratio, hardness and heat resistance qualities has been witnessed. New developments in the field of material science have led to new engineering metallic materials, composite materials and high tech ceramics having good mechanical properties and thermal characteristics as well as sufficient electrical conductivity so that they can readily be machined by spark erosion. Non-traditional machining has grown out of the need to machine these exotic materials.

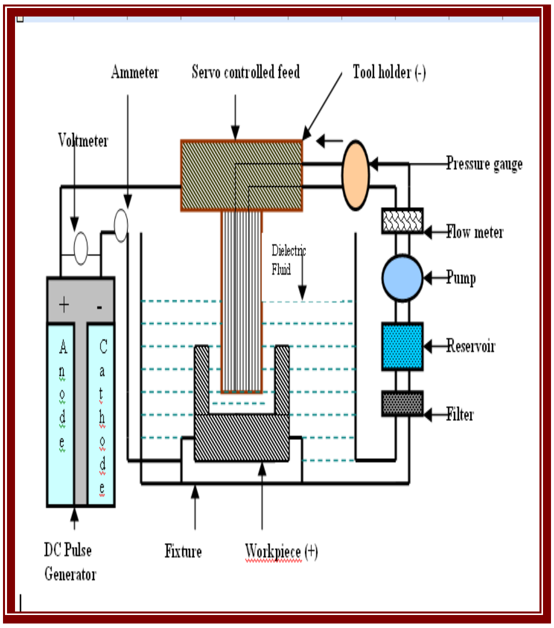

Fig. 1 Schematic of EDM Process

1.1 Components of EDM

1. Work-piece-all the conductive material can be worked by EDM

2. Tool Electrode-The EDM electrode is the tool that determines the shape of the cavity to be produce.

3. Dielectric fluid-The EDM setup consists of tank in which the dielectric fluid is filled. Electrode & wokpiece submersed into the dielectric fluid.

4. Servo system-The servo system is commanded by signals from gap voltage sensor system in the power supply and control the feed of electrode & workpiece to precisely match the rate of material removal.

5. Power supply-The power supply is an important part of any EDM system. It transform the alternating current from the main utility supply into the pulse direct current (DC) required to produce the spark discharge at the machining gap.

6. ***The DC pulse generator*** is responsible for supplying pulses at a certain voltage and current for specific amount of time.

1.2 Principle of EDM

The principle of EDM is to use the eroding effect of controlled electric spark discharges on the electrodes. It is thus a thermal erosion process. The sparks are created in a dielectric liquid, generally water or oil, between the workpiece and an electrode, which can be considered as the cutting tool. There is no mechanical contact between the electrodes during the whole process. Since erosion is produced by electrical discharges, both electrode and workpiece have to be electrically conductive. Thus, the machining process consists in successively removing small volumes of workpiece material, molten or vaporized during a discharge. The volume removed by a single spark is small, in the range of 10^{6}-10^{4} mm3, but this basic process is repeated typically 10’000 times per second. Figure 2 (a-e) gives a simple explanation of the erosion process due to a single EDM discharge. First, voltage is applied between the electrodes. This ignition voltage is typically 200 V. The breakdown of the dielectric is initiated by moving the electrode towards the workpiece. This will increase the electric field in the gap, until it reaches the necessary value for breakdown. The location of breakdown is generally between the closest points of the electrode and of the workpiece, but it will also depend on particles present in the gap. When the breakdown occurs, the voltage falls and a current rises abruptly. The presence of a current is possible at this stage, because the dielectric has been ionized and a plasma channel has been created between the electrodes. The discharge current is then maintained, assuring a continuous bombardment of ions and electrons on the electrodes. This will cause strong heating of the workpiece material (but also of the electrode material), rapidly creating a small molten metal pool at the surface. A small quantity of metal can even be directly vaporized due to the heating. During the discharge, the plasma channel expands. Therefore, the radius of the molten metal pool increases with time. The distance between the electrode and the workpiece during a discharge is an important parameter. It is estimated to be around 10 to 100 μm. (increasing gap with increasing discharge current). At the end of the discharge, current and voltage are shut down. The plasma implodes under the pressure imposed by the surrounding dielectric. Consequently, the molten metal pool is strongly sucked up into the dielectric, leaving a small crater at the workpiece surface.

A. ***Pre-breakdown***-voltage applied between the electrode and the workpiece

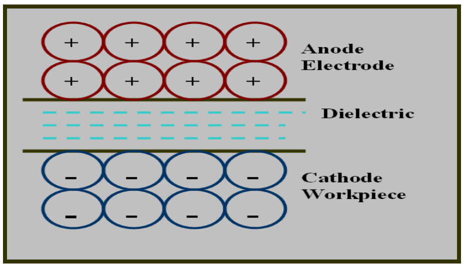

Fig.2

B. ***Breakdown***-Dielectric breakdown, creation of the plasma channel

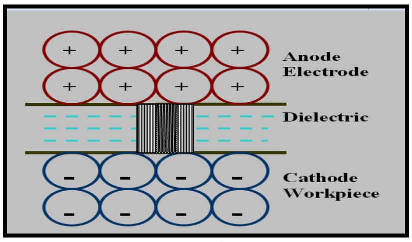

Fig.3

C. ***Discharge***-Heating, melting and vaporizing of the workpiece material

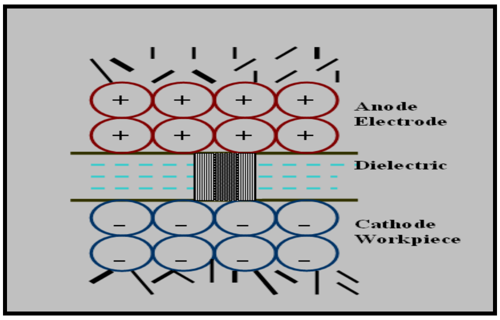

Fig.4

D. End of the discharge: plasma implosion, removing of the molten metal pool.

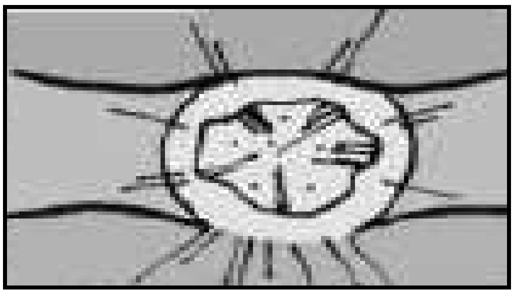

Fig.5

E. ***Post-discharge***-Solidifying and flushing of the eroded particles by the dielectric

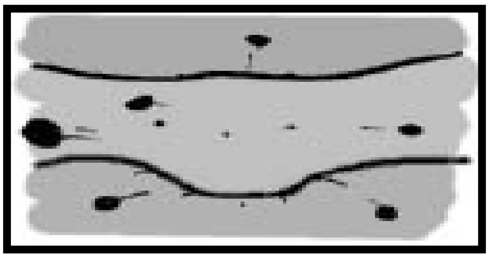

Fig.6

Fig.(2 -6) Principle of the EDM process

The liquid dielectric plays a crucial role during the whole process: it cools down the electrodes, it guarantees a high plasma pressure and therefore a high removing force on the molten metal when the plasma collapses, it solidifies the molten metal into small spherical particles, and it also flushes away these particles. The post-discharge is in fact a crucial stage, during which the electrode gap is cleaned of the removed particles for the next discharge. If particles stay in the gap, the electrical conductivity of the dielectric liquid increases, leading to a bad control of the process and poor machining quality. To enhance the flushing of particles, the dielectric is generally flowing through the gap. In addition, the electrode movement can be pulsed, typically every second, performing a large retreat movement. This pulsing movement also enhances the cleaning, on a larger scale, by bringing “fresh” dielectric into the gap. The material removal rate can be asymmetrically distributed between the electrode (*wear*) and the workpiece (*erosion*). The asymmetry is mostly due to the different materials of the electrodes. But it also depends on the electrode polarity, on the duration of the discharges and discharge current. Note that by convention, the polarity is called *positive* when the electrode is polarized positively towards the workpiece, *negative* otherwise. By carefully choosing the discharge parameters, 0.1% wear and 99.9% erosion can be achieved.

1.3 MAJOR PARAMETERS OF EDM

EDM Parameters mainly classified into two categories.

1. Process Parameters 2. Performance Parameters

1. Process Parameters

The process parameters in EDM are used to control the performance measures of the machining process. Process parameters are generally controllable machining input factors that determine the conditions in which machining is carried out. These machining conditions will affect the process performance result, which are gauged using various performance measures.

A. Electrical Parameters

1. Polarity
2. Discharge voltage
3. Gap Voltage
4. Peak Current
5. Average Current
6. Pulse on Time
7. Pulse off time
8. Pulse Frequency
9. Pulse waveform
10. Electrode Gap
11. Duty Factor

B. Non-Electrical Parameters

1. Electrode lifts time
2. Working Time
3. Nozzle flushing
4. Gain
5. Type of Dielectric

C. Powder Based Parameters

1. Powder type
2. Powder concentration 3.Powder size
4. Powder conductivity
5. Powder density

D. Electrode Based Parameters

1. Electrode material 2. Electrode size
3. Electrode shape

2. Performance Parameters-These parameters measure the various process performances of EDM results.

Table-1 Performance Parameters

Performance measure	**Process performance result**
Material removal rate (MRR)	MRR is a performance measure for the erosion rate of the workpiece and is typically used to quantify the speed at which machining is carried out. It is expressed as the volumetric amount of workpiece material removed per unit time.
Tool wear rate (TWR)	TWR is a performance measure for the erosion rate of the tool electrode and is a factor commonly taken into account when considering the geometrical accuracy of the machined feature. It is expressed as the volumetric amount of tool electrode material removed per unit time.
Wear ratio (WR)	WR is the ratio of TWR/MRR and is used as a performance measure for quantifying tool-workpiece material combination pairs since different material combinations gives rise to different TWR and MRR values. A material combination pair with the lowest WR indicates that the tool-workpiece material combination gives the optimal TWR and MRR condition.
Surface quality (SQ)	Surface quality is a broad performance measure used to describe the condition of the machined surface. It comprises components such as surface roughness (SR), extent of heat affected zone (HAZ), recast layer thickness and micro-crack density.
Surface roughness (SR)	SR is a classification of surface parameter used to describe an amplitude feature, which translates to roughness of the surface finish. Of the many parameters available to quantify SR, the most commonly used in EDM are arithmetical mean surface roughness (*Ra*), maximum peak-to-valley surface roughness (*Rmax*) and root mean square surface roughness (*Rq*).
Heat affected zone	HAZ refers to the region of a workpiece that did not melt

(HAZ)	during electrical discharge but has experienced a phase transformation, similar to that of heat treatment processes, after being subjected to the high temperatures of electrical discharge.
Recast layer thickness	The recast layer refers to the region of resolidified molten material occurring as the topmost layer of the machined surface. The recast layer is usually located above the heat affected zone.

1.4 Types of EDM

Basically, there are two types of EDM

1.4.1 Die-sinking

Die Sinker EDM, also called cavity type EDM or volume EDM consists of an electrode and workpiece submerged in an insulating fluid such as, more typically, oil or, other dielectric fluids. The electrode and workpiece are connected to a suitable power supply. The power supply generates an electrical potential between the two parts. As the electrode approaches the workpiece, dielectric breakdown occurs in the fluid, forming a plasma channel, and a small spark jumps.These sparks usually strike one at a time because it is very unlikely that different locations in the inter-electrode space have the identical local electrical characteristics which would enable a spark to occur simultaneously in all such locations. These sparks happen in huge numbers at seemingly random locations between the electrode and the workpiece. As the base metal is eroded, and the spark gap subsequently increased, the electrode is lowered automatically by the machine so that the process can continue uninterrupted. Several hundred thousand sparks occur per second, with the actual duty cycle carefully controlled by the setup parameters.

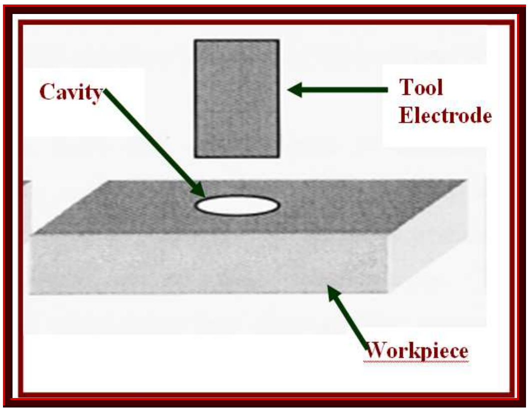

Fig.7 Die Sinking EDM

1.4.2 Wire-cut EDM

Wire EDM Machining (also known as Spark EDM) is an electro thermal production process in which a thin single-strand metal wire (usually brass) in conjunction with de-ionized water (used to conduct electricity) allows the wire to cut through metal by the use of heat from electrical sparks. A thin single-strand metal wire, usually brass, is fed through the workpiece, submerged in a tank of dielectric fluid, typically deionized water. Wire-cut EDM is typically used to cut plates as thick as 300mm and to make punches, tools, and dies from hard metals that are difficult to machine with other methods. Wire-cutting EDM is commonly used when low residual stresses are desired, because it does not require high cutting forces for removal of material. If the energy/power per pulse is relatively low (as in finishing operations), little change in the mechanical properties of a material is expected due to these low residual stresses, although material that hasn't been stress-relieved can distort in the machining process. Due to the inherent properties of the process, wire EDM can easily machine complex parts and precision components out of hard conductive materials. Wire EDM process produces burr-free machining and provided that the work-piece is electrically conductive its mechanical properties (hardness, toughness, brittleness, and ductility) impose no limitations on the machining process.

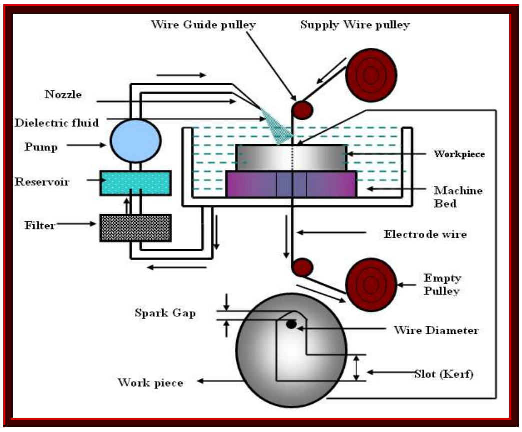

Fig. 8 wire cut EDM

II-VIBRATION, ROTARY& VIBRO-ROTARY BASED EDM

In this section various types of approach of researcher like vibration, rotary & vibro rotary mechanism based electric discharge machining Process which enhancement of MRR & reduction tool Wear & reduced machining cost.

2.1 Research progress in vibration rotary & Vibro-Rotary EDM

Table-2

Researcher Contribution year wise
Sato et al. (1987) Developed an EDM for micro-hole boring. They claimed that electrode rotation served as an effective gap flushing technique, yielding better material removal.
Murti and Philip (1987) added that with the combination of ultrasonic vibration in EDM the MRR and surface finish improved & TWR increased.
Soni & Chakraverti (1994) 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.
Zhang et al. (1997) Spark erosion with ultrasonic frequency using a DC power supply instead of the usual pulse power supply. The pulse discharge is produced by the relative motion between the tool and work piece simplifying the equipment and reducing its cost. It is easy to produce a combined technology which benefits from the virtues of USM and EDM.
Guo Z.N. et al. (1997) The higher efficiency achieves by the Employment of ultrasonic vibration is mainly attributed to the better circulation of dielectric and debris removal from work piece.
Soni and Chakraverti (1997) 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 TWR but the surface finish was improved.
Egashira et al. (1999) adopted to vibrate the work piece during machining. Micro holes as small as 5 µ 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.
Yan et al. (2000) optimized the cutting of Al_2O_3/6061Al composite using rotary EDM 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 Performance are MRR, 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.
Ghoreishi and Atkinson (2002) compared the effects of high and low frequency forced axial vibration of the electrode, rotation of the electrode and combinations of the methods (vibro-rotary) in respect of MRR, TWR & SQ in EDM die sinking and found 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.
Zhang et al. (2002) The increase in open voltage, pulse duration, amplitude of ultrasonic vibration and decrease of wall thickness of the pipe can give an increase of the MRR. He also found that oxygen gas can produced greater MRR than air.
Mohan et al.(2004) centrifugal force generate a layer of dielectric in to the machining gap, induces an atmosphere for better surface finish, prevent arching and improves material removal rate.
Kuo et al. (2004) 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.
Zhang et al. (2005) found that Material Removal rate. with the same surface roughness UEDM in gas is nearly twice as much as EDM in gas but less than the conventional EDM
Prihandana et al. (2006) 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.
Shih et al. (2007) EDG of AISI D2 tool steel work piece using a rotary disk copper electrode Mounted on horizontal spindle. It was observed that Higher MRR & lower electrode wear.
Chattopadhyay et al. (2008) 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.
Han et al. [2009] proposed a novel high speed EDM milling method using moving arc. They connected a copper electrode rotating rapidly around its axis and a workpiece to a DC power supply to generate a moving electric arc. The electrode was shaped like a pipe in order to ensure a high relative speed of any point on the electrode with respect to the workpiece. It was found that the MRR of EDM milling is almost four times greater than that of traditional EDM without any deterioration in surface roughness. The increase in MRR is due to enhanced duty cycle during EDM milling.
Xu et al. [2009] introduced a new kind of electrical discharge machining technology named tool electrode ultrasonic vibration assisted electrical discharge machining in gas medium. In This technology result showed that MRR could be increased greatly by introducing ultrasonic vibration. The comparison of MRR in traditional EDM in gas and ultrasonic vibration assisted gas medium EDM for machining cemented carbides workpiece was reported. MRR was found considerably higher for a particular discharge pulse-on time for ultrasonic vibration assisted machining.
G. S. Prihandana et al. [2011] application of low-frequency vibration in EDM process can be used to increase the MRR, and decrease the SR and tool wear rate (TWR).

2.1 Conclusion

Vibration, rotary and vibro-rotary mechanism makes the equipment simple and increases the material removal rate, provide better surface finish ejection from work piece. Better circulation of dielectric fluid and debris removal from work piece.

III- WATER IN EDM

Water as dielectric is an alternative to hydro carbon oil. The approach is taken to promote a better health and safe environment while working with EDM. This is because hydrocarbon oil such as kerosene will decompose and release harmful vapour (CO and CH4).

3.1 Research progress by using water as dielectric fluid

Table-3

Year	Researcher Contribution
1981	Jeswani M.L [1981]: Machining in distilled water resulted in higher MRR and lower wear ratio than in kerosene when high pulse Energy range was used.
1984	S. Tariq Jilani et al [1984]: The best machining rates have been achieved with tap water as the dielectric medium; zero TWR possible when using Cu tool with negative polarities.
1987	Koenig W. et al [1987]: The erosion process in water based media consequently possesses higher thermal stability & much higher power input can be achieved especially under critical condition. Use aqueous solution of organic compounds as medium for

	EDM sinking almost completely excludes any fire hazard, permitting safe operation of plant.
1993	Koenig W. et al [1993]: EDM sinking process can be made more cost effective through the use of water based media, significantly improving competitiveness with other process. Yoshiro et al [1993]: A machine tool maker has established technologies for water-immersion machining, greatly improved the surface finish so that post process manual polishing is not required.
1995	Kruth J.P et al [1995]: Water dielectric cause decarbonisation in the white layer at the surface of a work piece while oil dielectric increase the carbon content in the white layer appears as iron carbide in columnar.
1999	Chen S.L. et al [1999]: The MRR is greater and the relative wear ratio is lower when machining in distilled water rather than in kerosene.
2004	Leao & Pashby [2004]: Water based dielectrics may replace oil-based fluids in die sinking applications.
2005	Yan B.H. et al [2005]: TiN was synthesized on the machined surface by chemical reaction that involved elements obtained from the work piece and the urea solution in water as dielectric during EDM: the surface modification of pure titanium metals exhibited improved friction and wear characteristics. Ekmekci. B. et al [2005]: Stresses are found to be increasing rapidly with respect to depth, attaining to its maximum value around the yield strength and then fall rapidly to compressive residual stresses in the core of the material since the stresses within plastically deformed layers are equilibrated with elastic stresses. Kang & Kim [2005]: In the case of the kerosene electrical discharge (ED) machined specimens, it was observed that carburization and sharp crack propagation along the grain boundary occurred after the heat treatment. However, the deionized ED machined specimen after the heat treatment underwent oxidation and showed no crack propogation behaviour. Sharma A. et al. [2005] investigated the potential of electrically conductive chemical vapor deposited diamond as an electrode for micro-electrical discharge machining in oil and water. While doing a comparative study on the surface integrity of plastic mold steel,
2008	Han-Ming Chow et al. [2008] using pure water as an EDM dielectric fluid for titanium alloy yields a high MRR and relatively low electrode wear and small expanding-slit by employing negative polarity (NP) processes.

3.2 Conclusion

Water-based dielectric can replace hydrocarbon oils since it is environmentally safe. Water based EDM is more eco friendly, reduced harmful agent, toxic fumes dangerous for human & economically low cost machining as compared to conventional oil based dielectric. The material removal rate enhanced with use of water.

IV- DRY EDM

Dry EDM is a green environment friendly Electric discharge machining Technique in which the liquid dielectric is replaced by a gaseous dielectric. Gas at high pressure as used as the dielectric medium. In dry EDM, tool electrode is formed to be thin walled pipe. The flow of high velocity gas into the gap facilitates removal of debris and prevents excessive heating of the tool and work piece at the discharge spots. Tool rotation during machining not only facilitates flushing but also improves the process stability by reducing arcing between the electrodes The technique was developed to decrease the pollution caused by the use of liquid dielectric which leads to production of vapor during machining and the cost to manage the waste. Dry EDM method with the shortest machining time compare to oil die sinking EDM, & lowest electrode wear ratio. Work removal rate also get enhanced by dry EDM.

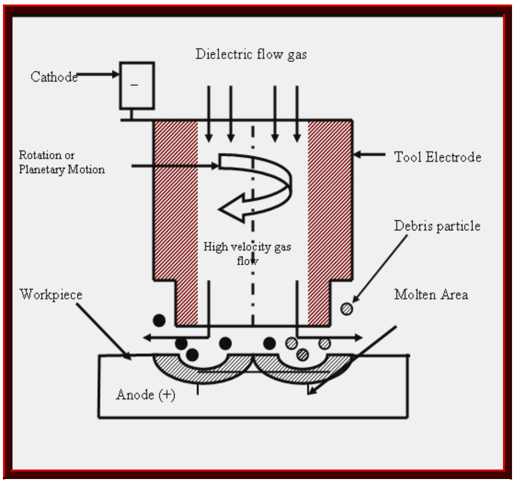

Fig. 9 Principle of Dry EDM

4.1 Research Progress in Dry EDM

Table-4

Researcher contribution Year wise
Kunieda et. al. [1991]: oxygen gas introduced in discharge gap based dielectric in water increased removal rate.
Kunieda et al [1997]: Electrical discharge machining can be achieved in gas.
Yoshida et al [1999]: tool electrode is almost negligible for any pulse duration in dry EDM.
Kunieda et al [2001]: narrower gap, no corrosion of work piece and high finish cutting in dry EDM.
Zhang et al [2002]: EDM with ultrasonic aid (UEDM) can be achieved in gas medium.
Wang et al [2003]: dry EDM removes environmental pollution due to liquid dielectric. Better straightness with dry EDM. Kunieda et al [2003]: oxidation of work pieces due to the usage of oxygen electrode wear is almost negligible increase MRR. Curodeau et al [2003]: a thermoplastic composite electrode used in dry EDM using air as dielectric medium. Z. B. Yu et al [2003]: dry EDM is suitable for 3D milling of difficult to cut materials such as cemented carbide.
Kunieda et al [2004]: improvement of dry EDM by controlling the discharge gap using a piezoelectric actuator. Wang T. et al [2004]: the explosive force and electrostatic force acting on wire electrode decrease in dry WEDM. Zhang et al [2004]: ultrasonic vibration improves MRR in gas by increasing the effective discharge. Li L.Q [2004]: discharge passage extends rapidly in the gas medium of dry EDM.
Zhang et al [2005]: a theoretical model of surface roughness in ultrasonic vibration assisted EDM (UEDM) in gas.
ZhanBo et al. [2006]: Optimum combination of depth of cut, gas pressure & pulse duration 25µm it is lead to maximum material removal rate & minimum tool wear.
Shue k. Y. et al. [2010]: Dry Electrical discharge machining (Dry EDM), using gas as dielectric, has been developed to solve problems against environment. It has both advantages of high material removal ratio (MRR) and low relative electrode wear ratio (REWR
Masahiro Fujiki [2011]: Achieve high material removal rate in tool path planning for the near-dry electrical discharge machining (EDM) milling process using tubular electrode with a lead angle.
Wang T. et. al. [2013]: Main advantages of dry finishing of WEDM such as better straightness, lower SR and shorter gap length.
Roth R. et al. [2013]: Heat energy from the oxidation has only a little effect on the material removal rate and that the main difference between oxygen and less oxidizing gases is to find in different stability and time efficiency of the process.

4.2 Conclusion

Dry EDM is eco friendly machining. Pollution is reduced by use of gas instead of oil based dielectric. Harmful & toxic fumes are not generated during machining. Material removal rate &electrode wear ratio also get enhanced by dry EDM. This technique should be supported and more investigation should be made since it helps to save the environment.

V- POWDER MIXED EDM

Powder mixed electric discharge machining (PMEDM) is one of the new innovations for the enhancement of capabilities of electric discharge machining process. In this process, a suitable material in fine powder is properly mixed into the dielectric fluid. The added powder improves the breakdown characteristics of the dielectric fluid. The insulating strength of the dielectric fluid decreases and as a result, the spark gap distance between the electrode and work piece increases. Enlarged spark gap distance makes the flushing of debris uniform. This results in much stable process thereby improving material removal rate and surface finish.

When voltage is applied the powder particles become energized and behave in a zigzag fashion. These charged particles are accelerated due to the electric field and act as conductors promoting breakdown in the gap. This increases the spark gap between tool and the work piece. Under the sparking area, these particles come close to each other and arrange themselves in the form of chain like structures. The interlocking between the powder particles occurs in the direction of flow of current. The chain formation helps in bridging the discharge gap between the electrodes. Because of bridging effect, the insulating strength of the dielectric fluid decreases resulting in easy short circuit. This causes early explosion in the gap and series discharge' starts under the electrode area. The faster sparking within a discharge causes faster erosion from the work piece surface and hence the material removal rate increases.

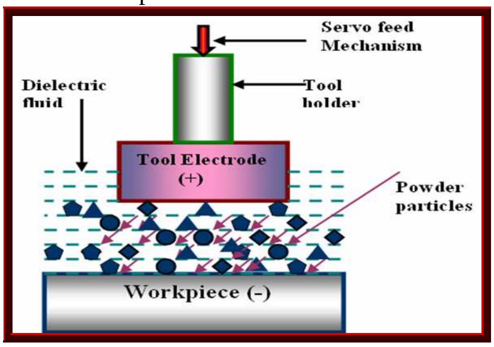

Fig.10 working principle of PMEDM

5.1 Research Progress in Powder mix Dielectric Electric discharge Machining (PM-EDM)

Table-5

Author/year	Process parameters	Tool Electrode	Workpiece	Research finding
Ming, Q.Y. et al. (1995)	Current Pulse width, Pulse interval, Additives powder concentration	Copper	high-carbon steel	• The surface roughness decreased with increase in powder concentration, but increased with excessive powder concentration. • The tendency for crack inception and extent of crack propagation on the machined surface was reduced. • The recast layer was thinner and denser
Tzeng, Y.F. et al. (2001)	Aluminium chromium copper & silicon carbide powders concentration	Copper	SKD-11	• The discharge gap distance and material removal rate increased as powder granularity was increased. • Of the powder materials capable of remaining in suspension during machining, aluminium produced the largest discharge gap enlargement and silicon carbide produced the smallest.
Zhao, W.S.,	Pulse on time	Copper	Steel	• PMD-EDM was applied to improving

et al. (2002)	Peak current Discharge gap Pulse width Concentration of Al powder		workpiece	the efficiency of rough machining. • PMD-EDM enabled a 70 % improvement in machining efficiency over EDM in powder-free dielectric while achieving similar machined surface roughness
Pecas p. et al. (2003)	Peak current Duty Cycle Polarity Flushing Concentration of Si powder	Electrolytic Copper	AISI H13	• The positive influence of the Si powder in the reduction of the operating time, achieve a specific SQ, and in the decrease of the SR, allowing the generation of mirror-like surfaces.
Klocke, F., et al. (2004)	Polarity Voltage Pulse duration Duty Cycle Concentration of Al,& Si powder.	Tungsten electrodes	Inconel 718 superalloy	• The powder additives caused greater expansion of plasma channel compared to a powder-free dielectric. • The powder additives changed the thermal material removal mechanism and affected the composition and morphology of the recast layer.
Tzeng, Y.F. et al. (2005)	Peak current Pulse on time Duty cycle Powder size, Powder Concentration of Al. Cr Cu, Si.	Copper	SKD-11	• The presence of powder additives reduced the recast layer thickness. • The surface roughness decreased when aluminium powder granularity was decreased. • The RLT decreased when aluminium powder granularity was increased. • Aluminium powder material produced the smallest surface roughness and thinner recast layer.
Kansal et al. (2005)	Pulse on time, Duty cycle, Peak current, Concentration of the added Si powder	Copper	EN 31 tool steel	• MRR increased with the increase in the concentration of silicon powder. • Surface roughness improves with increased concentration of silicon powder.
Kansal H. K. et. al. (2006)	Peak current, pulse duration, Duty cycle, Concentration of silicon powder	Copper	H-11 Die Steel	• The concentration of Added silicon powder, pulse duration, & peak current significantly affect the material removal rate & Surface roughness in powder mix electrical discharge machining. • Addition Of appropriate quantity of silicon powder into dielectric fluid of EDM enhances the material erosion rate.
Kansal H. K. et. al. (2007)	peak current, pulse on time, pulse-off time, concentration of powder, gain, and nozzle	Copper	AISI D2 Die Steel	• The concentration of Si powder into the dielectric fluid of EDM appreciably enhances material removal rate. • Peak current, concentration of the Si powder, pulse-on time, pulse-off time, & gain significantly affect the MR in

	flushing			PMEDM. • The nozzle flushing when applied at the interface of tool electrode and workpiece does not significantly affect the MR.
Furutani, K., et al. (2009)	Discharge current, Pulse duration, Concentration of Titanium Powder	copper	Titanium carbide	• PMD-EDM was applied to accretion process. • Deposition of TiC was possible at discharge energies below 5 mJ under certain discharge current and pulse on time combinations. • There existed a maximum discharge current for deposition. • The larger the discharge current, the smaller the range of pulse on time durations available for deposition.
Sharma s. et al. (2010)	concentration of Al. powder and the grain size of the Powder particles, Reverse Polarity Current, voltage, pulse on time, duty cycle	Copper	Hastelloy	• The surface roughness of the work material continuously decreases with the increase in the concentration of aluminium powder and with change in the grain size of the powder particles. • With the increase in the concentration of the powder, percentage wear rate decreases sharply. • With change in the grain size of the powder, the percentage wear rate decreases continuously. • With the increase in the concentration of additive powder in the dielectric fluid, the tools wear increases. • With the addition of aluminium powder in the dielectric fluid of EDM, the material removal rate increases.
Singh P. et al. (2010)	Concentrations of aluminum powder and grain size of powder	Copper electrode.	Hastelloy	• The addition of Al powder in dielectric fluid increases MRR, decreases TWR and improves surface finish of Hastelloy.
Singh G. et al. (2012)	Polarity, peak Current, pulse on time, duty Cycle, gap Voltage, Concentration of abrasive Powder	Copper	H 13 steel	• Negative polarity of tool electrode is desirable lowering of surface roughness. • Increasing pulse on time leads to produce more rough surfaces. • Addition of powder particles in dielectric fluid decreases surface roughness of specimen in EDM process. • Higher peak currents produce more rough surfaces in EDM process.
Syed & Palaniyandi	peak current, pulse on-time,	electrolytic copper,	W300 die-steel	• Uses distilled water mixed with aluminium powder improve the

(2012)	Polarity, Concentration of Al powder,			performance of MRR, SR & WLT. • High MRR, is obtained in positive polarity, whereas better surface quality (surface roughness and white layer thickness) is achieved in negative polarity. Hence for rough machining positive polarity can be selected to achieve higher MRR and during finishing a better surface is achieved by changing the polarity.
Mathapathi U. et al. (2013)	Pulse on time, Pulse off time Peak current Tool electrode lift time, Concentration of graphite & Cr powder	Copper	ASI D3/HCHCR	• TWR in PMEDM is smaller as compared with the conventional EDM. • MRR has increased by adding the powder in dielectric fluid as compared with conventional EDM. • MRR is maximum effected by the increase of peak current. • MRR has been decreased by increasing the pulse off time. • As the tool electrode lift time has increased, the MRR.
Muniu J.M. et al. (2013)	Concentration of Copper, Diatomite, Aluminium	Graphite	Mild steel	• MRR for copper, aluminium and diatomite powder increases to maximum and then decreases with further increase in powder concentration.
Goyal S. et al.(2014)	Current, Voltage, Pulse on time, Duty factor Grain size of Al. powder & Concentration of Al powder	Copper	AISI 1045 steel	• Mixing of Aluminium (Al) powder in Di-electric fluid ensures improved Metal removal rate and surface finishing.

5.2 Conclusion

Use of powder mix in electrolyte provide mirror like surface finish, increase in material removal rate, Totally Burr free ,& no stresses produced in work piece. Proper work piece and powder combination must be used for better results.

VI- FUTURE EDM RESEARCH DIRECTION

The EDM research area can be divvied into four different major areas.

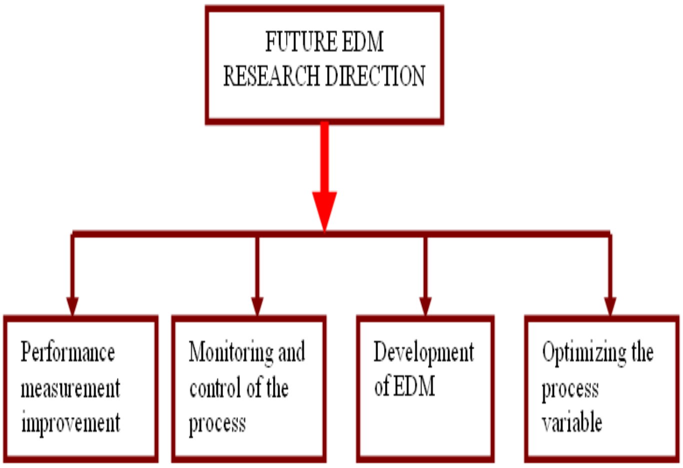

Fig. 11 Classification

6.1 Performance measurement improvement

This can be done by the use of CNC to EDM for facilitating the MRR and improving the tool wear compensation techniques, it results the potential of using simple tooling to generate complex 3D cavity without employing a costly 3D profile electrode. This technique benefits the EDM process by reducing the large proportion of cost and time factors of producing the electrode which account for almost 45% of the total machining cost.

6.2 Monitoring and control of the process

The monitoring and control of the EDM process are often based on the identification and regulation of adverse condition occurring during the sparking process. Most of the approaches measure pulse and time domain parameters to differentiate the arc pulses from the rest EDM pulses. The option of using emitted RF has also been experimented but generates very little research. The application of fuzzy logic to the adaptive control system provides a reliable pulse discriminating role during the EDM process. Several authors claimed that the fuzzy logic control implements a control strategy that is adopted by a skilled operator to maintain the desired machining process. Tarng et al. [1997] suggested a fuzzy pulse discriminator established on the linguistic rules acquired from the knowledge of experts and expressed mathematically through the theory of fuzzy sets. However, the definition of membership functions for each fuzzy set is not straightforward and is based on exploratory means to classify various discharge pulses. Radio frequency (RF) or HF signal generated during EDM has been used to monitor and control the sparking process. Radio Frequency monitoring system providing a pulse control to the machine power generator by examining the RF signal created from the spark gap. The RF monitoring system detects any drop in the intensity of signals to a threshold value whenever the discharge changes from sparking to arcing.

6.3 Development of EDM

With the help of different advances in the EDM machine has increased the applications of EDM process. It is used in the automotive industry, aerospace industry , nuclear industry, mould, tool and die making industries. EDM is also used in machining of medical, dental, optical equipments, jewellery industries. For this we need the machining req. such as the machining of HSTR materials, which generate strong research interest and increase the EDM machine manufacturers to improve the machining characteristics. One of the unique options of improving the machining performance involves the HMP combining EDM process with other material removal processes. The most popular and highly effective arrangement includes the USM delivering ultrasonic vibration to the electrode, which assists the sparking and flushing operations. However, Taylan et al. [2001] noted that the current trend in tool and die manufacturing is towards replacing the EDM process with new machining techniques such as HSM. HSM process is just as capable as the EDM process in machining hardened materials with 40–60 HRC. Therefore, HMP involving EDM will continue to draw intense research interests seeking innovative ways of improving the machining performance and expanding the EDM applications

6.4Optimizing the process variable

In these days, the most effective & economically machining approach is determined by finding the different factors affecting the EDM process and tries to find the ways of obtaining the optimum machining condition and performance. In this categories provide a study of several machining strategies including design of the process parameters & modeling of the EDM Process. The EDM process has a very strong stochastic nature. Due to the complicated discharge mechanisms making it difficult to optimize the sparking process. The optimisation of the process often involves relating the various process variables with the performance measures maximising the MRR, while minimising the TWR and yielding the desired SR. In many cases, S/N ratio together with the help of analysis of variance (ANOVA) technique we measure the amount of variation from the desired performance and find out the various important process variables affecting the process response.

VII- MAJOR RESEARCH DEVELOPMENT IN EDM RESULTING IN MRR IMPROVEMENT

In this paper, review of EDM research work related to MRR improvement has been presented along with some insight into the basic Electric Discharge machining (EDM) process MRR mechanism. The major research development resulting in improvement in material removal rate (MRR) & Reduction tool wear is summarized in Table-6.

Table-6

S. No.	Researcher contribution year wise	Workpiece material	Electrode material	Electrical Parameters	Non-Electrical parameters
1.	Bayramoglu and Duffill (1995) Investigated frame type cutting tool with CNC EDM for generation of linear, circular and curved contours.	Mild steel	Copper	Voltage, current, on- time, off -time	Non
2.	Ming and He (1995), Investigated the effect of powder suspension in kerosene oil used as dielectric.	High carbon steel and high alloy steel	Copper	Current, pulse interval	Non
3.	Wong et al. (1995) Investigated the influence of flushing on the efficiency and stability of machining condition.,	AISI 01 tool steel	Copper	Voltage, current, pulse duration, polarity	Flushing rate
4.	Kunieda and Yoshida, (1997) Investigated dry EDM method and compared its performance with EDM in oil.	Steel (S45C)	Copper	Voltage, current, Pulse duration, polarity	Wall thickness of pipe electrode, air pressure, rotation and plenary motion of tool
5.	Wong et al.,(1998) Investigated the near mirror-finish phenomenon in EDM with fine powder suspension in dielectric.	SKH-54 tool steel	copper	Spark gap, pulse duration, polarity	Powder suspension type and properties
6.	Chen et al.,(1999) Investigated Machining characteristics with kerosene and distilled water as the dielectrics.	Titanium alloy (Ti–6A1–4V)	Copper	Current, pulse duration	Type of dielectric fluid
7.	Wang and Yan.,(2000) Compared the performance of	Al2O3/6061 Al	Copper	polarity, peak current,	Electrode rotation,

	stationary electrode, a rotational electrode, and a rotational electrode with an eccentric through-hole terms of machining characteristics.	composite		pulse duration, supply voltage	flushing pressure
8.	Kunieda and Muto (2000) Investigated and compared machining characteristics of Multi-spark EDM electrode with those of conventional EDM electrode.	steel SUJ2	Copper	Voltage, current, polarity	Non
9.	Aspinwall (2001) Investigated hybrid high speed machining process (EDM/HSM).	Steel	Graphite	Voltage	Electrode rotation
10.	Tzeng and Lee (2001) Investigated the effects of various powder characteristics on the efficiency of PMEDM.	SKD11	Copper	Spark gap, current, pulse-on time	Powder suspension type
11.	Zhao et al.(2002) Performed Experimental research on Machining efficiency and Surface roughness of PMEDM in rough machining.	Steel	Copper	Current, pulse-on time, pulse-off time	Non
12.	Ghoreishi and Atkinson (2002) Investigated and compared the effect of high and low frequency forced axial vibration, electrode rotation and combination of these methods on performance measures.	Tool and die steel A1S1 01	Copper	Open voltage, Discharge voltage, tool polarity	Amplitude of ultrasonic and low frequency vibration, electrode rotation, Frequency of vibration
13.	Zhang et al.(2002) Proposed and Investigated ultrasonic vibration Electrical discharge machining	Steel	Copper	Voltage, pulse duration,	Pipe wall thickness, electrode, vibration amplitude, effects of gas medium
14.	Kunieda et al.(2003) Investigated high speed EDM milling of 3D cavities using gas as the working fluid	Mild steel (SS400)	Copper	Discharge current, discharge duration, discharge interval	Non
15.	Mohan et al. (2004) Investigated Effect of tube electrode rotation on performance measures.	6025 Al-alloy reinforced with SiC particles	Brass	Peak current, polarity, pulse duration	Electrode rotation, volume fraction of SiC reinforced particles, hole diameter of tube electrode
16.	Bayramoglu and Duffill (2004) Investigated plate type tool and compared the	Steel	Copper	Voltage, current, on- time,	Non

	performance with 3 D form tool.			off -time	
17.	Yu et al.(2004) Compared Machining characteristics between dry EDM milling, oil EDM milling and oil die sinking EDM	Cemented carbide	Copper tungsten	Discharge current, discharge duration, discharge interval	Electrode rotation
18.	Singh et al. (2005) Optimize the Process parameters of powder mixed electrical discharge machining by using response surface methodology.	EN 31 tool steel	Copper	Pulse on time, Duty cycle, Peak current	Concentration of the added silicon powder
19.	Zhang et al. (2006) Applied ultrasonic to improve the efficiency in EDM in gas medium	AISI 1045 steel	Copper	Open voltage, Pulse duration, Discharge current	Gas pressure, Wall thickness, actuation amplitude
20.	Kansal et al. (2006) Performance parameters optimization (multi characteristics) of powder mixed Electric discharge Machining (PMEDM) Through Taguchi's method utility concept.	H-11 Die Steel	Copper	Peak current, pulse duration, Duty cycle,	Concentration of silicon powder
21.	Kansal et al. (2007) Effect of Silicon Powder Mixed EDM on Machining Rate of AISI D2 Die Steel	AISI D2 Die Steel	Copper	peak current, pulse on time, pulse-off time,	concentration of powder, gain, and nozzle flushing
22.	Chen et al.(2008) Introduced a New mechanism of cutting pipe combined with electrical discharge machining	SUS 304	Copper	Peak current, pulse duration, polarity	Workpiece rotation
23.	Han et al. (2009) Proposed a Novel high speed electrical discharge machining (EDM) milling method using moving electric arcs.	Mold steel	Copper	Open voltage, Peak current, Duty cycle	Electrode revolution
24.	Xu et al. (2009) Proposed the tool electrode ultrasonic Vibration assisted EDM in gas medium and introduced its principle.	YT15 cemented carbide	Copper	Voltage, current pulse on time	Frequency And amplitude of ultrasonic vibration,
25.	S.H. Tomadi et. al. (2009) Analysis of the Influence of EDM Parameters on Surface Quality Material Removal Rate and Electrode Wear of Tungsten Carbide.	Tungsten Carbide (WC-Co)	Copper tungsten	peak current, power supply voltage, Pulse on time, pulse off time.	Non
26.	Iqbal & Khan (2010)	Stainless	Copper	Voltage &	Rotational speed of the

	Influence of Process Parameters on Electrical Discharge Machined Job Surface Integrity.	steel AISI 304		feed rate	electrode
27.	B. Sidda Reddy et. al. (2010) Parametric study of electrical Discharge machining of ASI304 Stainless steel.	Stainless steel AISI 304	Copper	Current, Open circuit-voltage, Servo and duty cycle.	Non
28.	Kuldeep Ojha et. al. (2011) Parametric Optimization of PMEDM Process using Chromium Powder Mixed Dielectric and Triangular Shape Electrodes.	EN-8 steel	copper	Average current, duty cycle,	Angle of electrode and concentration of chromium powder added into dielectric fluid of EDM
29.	Shabgard1 M. et. al. (2011) Influence of Input Parameters on the Characteristics of the EDM Process.	AISI H13 tool steel	copper	Pulse on-time and pulse current.	Non
30.	Harpuneet Singh (2012) Investigating the Effect of Copper Chromium and Aluminum Electrodes on EN-31 Die Steel on Electric Discharge Machine Using Positive Polarity.	EN-31 die steel	Copper chromium and Aluminum	pulsed current Positive Polarity	Non
31.	Vishwakarma M. et. al.(2012) Response surface approach for optimization of Sinker Electric Discharge Machine process parameters on AISI 4140 alloy steel	AISI 4140 Grade steel alloy.	Copper	Discharge current Pulse-on time Duty Cycle Gap Voltage	Flushing Pressure
32.	Syed & Palaniyandi (2012) Performance of electrical discharge machining using aluminium powder suspended distilled water	W300 die-steel	electrolytic copper,	peak current, pulse on-time, Polarity	concentration of the powder,
33.	Belgassim and Abusada (2012) Optimization of the EDM Parameters on the Surface Roughness of AISI D3 Tool Steel.	AISI D3 Tool Steel	Brass	Pulse current Pulse –on time Pulse –off time and Gap voltage	Non
34.	Gurule & Nandurkar (2012) Effect of Tool Rotation on Material Removal Rate during Powder Mixed Electric Discharge Machining of Die Steel.	Die steel D2	Cu, brass Al	Pulse current Pulse –on time Pulse –off time	Suspension of Al powder concentration, Tool rotation, Flushing pressure,
35.	Reza Atefi et. al., (2012) The Investigation of EDM Parameters in Finishing Stage	hot work steel DIN1.2344	Copper	pulse current, pulse	Non

	on Surface Quality Using Hybrid Model			voltage, pulse on-time, pulse off-time)	
36.	Bharti S. P .et al.,(2012) Multi objective optimization of electric discharge machining process using controlled elitist NSGA-II.	Inconel 718	Copper	Discharge Current Pulse-on time Duty cycle Gap Voltage	Shape factor (SF) Flushing pressure Tool Electrode Lift
37.	Singh G. et. al., (2012) effect of machining parameters on surface Roughness of H 13 steel in EDM process using Powder mixed fluid.	H 13 steel	Copper	Polarity, peak Current, pulse on time, duty Cycle, gap Voltage	Concentration of abrasive Powder
38.	M. Gostimirovic et al. (2012) Effect of electrical pulse parameters on the machining performance in EDM.	Manganese-vanadium tool steel	Graphite tool Electrode	Discharge current & pulse duration	non
39.	Khan F. et al. (2012) Experimental Investigation of Machining of Al/SiC MMC on EDM by using Rotating and Non-Rotating Electrode	Al/SiC MMC		pulse on time, pulse off time, voltage and peak current	Rotating and Non-Rotating Electrode
40.	S. Sivasankar et. al. (2013) Performance study of tool Materials and optimization of Process parameters during EDM On ZrB2-SiC composite through Particle swarm optimization Algorithm.	ZrB2-SiC composite	graphite, titanium niobium, tantalum and tungsten	pulse on time, pulse off time	Non
41.	Jai Hindus.S et. al. (2013) Experimental Investigation on Electrical discharge machining of SS 316L.	SS 316 L	Copper	Current Pulse –on Time	Non
42.	Balbir Singh et. al. (2013) Investigating the Influence of Process Parameters of ZNC EDM on Machinability of A6061/10% SiC Composite.	A6061/10% SiC Composite	copper	current, gap voltage, pulse-on time, and pulse-off time	non

43	Goyal S. et al.(2014) Parametric Study of Powder Mixed EDM and Optimization of MRR & Surface Roughness	AISI 1045 steel	Copper	Current, Voltage, Pulse on time, Duty factor	Grain size of Al. powder & Concentration of Al. powder

7. SUMMARY

Recent advancements in various aspects of electro-discharge machining that reflect the state of the art in these processes are presented in this review paper. Researcher works on enhancement of material removal rate (MRR), reduction of tool wear rate (TWR), improve Surface Quality (SQ) by experimental investigation. Various approaches like Vibration, rotary and Vibro-rotary mechanism based EDM, water based EDM has been employed for increase of EDM efficiency, Dry EDM use of gas instead of oil electrolyte, PM-dielectric Electric Discharge Machining. It also plays a significant role in medical, optical, Jewellery, automotive and aeronautic industry & making a various mechanical component in manufacturing industries.

REFERENCES

1. A. Curodeau, M. Richard, L. Frohn-Villeneuve, (2004):Molds surface finishing with new EDM process in air with thermoplastic composite electrodes, Journal of Materials Processing Technology 149, pp.278–283.
2. A. Sharma, M. Iwai, K. Suzuki, T. Uematsu (2005): Potential of electrically conductive chemical vapor deposited diamond as an electrode for micro-electrical discharge machining in oil and water, New Diamond and Frontier Carbon Technology 15, pp. 181–194.
3. A. Taylan, L. Blaine, Y.C. Yen (2001): Manufacturing of dies and molds, Ann. CIRP 50 No.2, pp. 405–423.
4. A.K.M. Asif Iqbal and Ahsan Ali Khan (2010): Influence of Process Parameters on Electrical Discharge Machined Job Surface Integrity, American J. of Engineering and Applied Sciences 3, No.2, pp. 396-402.
5. Aspinwall, D.K., Dewes, R.C., Burrows, J.M., Paul, M.A. (2001): Hybrid high speed machining (HSM): system design and experimental results for grinding/HSM and EDM/HSM". Ann. CIRP, 50 (1), 145–148.
6. B. Ekmekci, O. Elkoca, A.E. Tekkaya, A. Erden, (2005): Residual stress state and hardness depth in electric discharge machining: de-ionized water as dielectric liquid, Machining Science and Technology 9, pp. 39–61.
7. B. Sidda Reddy, et. al. (2010): Parametric study of electrical Discharge machining of ASI304 Stainless steel, International Journal of Engineering Science and Technology, 2(8), pp.3535-3550.
8. B.H. Yan, H.C. Tsai, F.Y. Huang,(2005):The effect in EDM of a dielectric of a urea solution in water on modifying the surface of titanium, International Journal of Machine Tools & Manufacture 45, pp.194–200.
9. Balbir Singh, Jatinder Kumar & Sudhir Kumar (2013):Investigating the Influence of Process Parameters of ZNC EDM on Machinability of A6061/10% SiC Composite, Advances in Materials Science and Engineering , volume 2013, Article ID 173427, 8 pages.
10. Bayramoglu, M., Duffill, A.W. (1995): Manufacturing linear and circular contours using CNC EDM and frame type tools, Int. J. Mach. Tools Manuf., 35(8), pp.1125–1136.
11. Bayramoglu, M.; Duffill, A.W. (2004): CNC EDM of linear and circular contours using plate tools, Journal of Materials Processing Technology, 148, pp.196–203.
12. Belgassim O. & Abusada A. (2012): Optimization of the EDM Parameters on the Surface Roughness of AISI D3 Tool Steel, Proceedings of the International Conference on Industrial Engineering and Operations Management Istanbul, Turkey, July 3 – 6, pp. 2306-2313.
13. Chattopadhyay,K.D.; Verma,S.; Satsangi,P.S.; Sharma,P.S.(2008): Development of empirical model for different process parameters during rotary electrical discharge machining of copper-steel(EN-8) system, Journal of Materials processing technology.
14. Chen, S.L., Lin, M.H., Hsieh, S.F., Chiou. S.Y. (2008): The characteristics of cutting pipe mechanism with multi-electrodes in EDM, Journal of materials processing technology, 203, pp.461– 464.
15. Chen, S.L., Yan, B.H., Huang, F.Y. (1999): Influence of kerosene and distilled water as dielectric on the electric discharge machining characteristics of Ti-6Al-4V", Journal of Materials Processing Technology, 87, 107–111.
16. Chow, H. M., Yang, L. D., Lin, C. T., Chen, Y. F. (2008):The use of SiC powder in water as dielectric for micro-slit EDM machining, journal of materials processing technology, 195, pp. 160–170.

17. Egashira, T. (1999): Micro ultrasonic machining by the application of work piece vibration, CIRP Annals— Manufacturing Technology, 48, pp. 131–134.
18. F.N. Leao, I.R. Pashby, (2004): A review on the use of environmentally friendly dielectric fluids in electrical discharge machining, Journal of Materials Processing Technology 149, pp.341–346.
19. Furutani K., Sato H. and Suzuki M. (2009):Influence of electrical conditions on performance of electrical discharge machining with powder suspended in working oil for titanium carbide deposition process. International Journal of Advanced Manufacturing Technology, 40(11), pp. 1093-1101.
20. Ghoreishi, M., Atkinson, J., (2002):A comparative experimental study of machining characteristics in vibratory, rotary and vibro-rotary electro-discharge machining, Journal of Materials Processing Technology, 120, pp.374–384.
21. Goyal S. & Singh R. K. (2014): Parametric Study of Powder Mixed EDM and Optimization of MRR & Surface Roughness, International Journal of Scientific Engineering and Technology, 3(1) pp.56-62.
22. Gurtej Singh, Paramjit Singh, Gaurav Tejpal & Baljinder Singh (2012):effect of machining parameters on surface Roughness of H 13 steel in EDM process using Powder mixed fluid, International Journal of Advanced Engineering Research and Studies, 2(1) , pp. 148-150.
23. G. S. Prihandana1, M. Mahardika1, M. Hamdi, & Kimiyuki Mitsui (2011): Effect of low-frequency vibration on workpiece in EDM processes, Journal of Mechanical Science and Technology, 25 (5) pp. 1231~1234.
24. Gurule N. B.& Nandurkar K. N. (2012):Effect of Tool Rotation on Material Removal Rate during Powder Mixed Electric Discharge Machining of Die Steel, International Journal of Emerging Technology and Advanced Engineering, 2, pp..328-332.
25. Han, F., Wang, Y., Zhou, M., (2009): High-speed EDM milling with moving electric arcs , Int. J. Mach. Tools Manuf., 49, pp.20–24.
26. Harpuneet Singh (2012):Investigating the Effect of Copper Chromium and Aluminum Electrodes on EN-31 Die Steel on Electric Discharge Machine Using Positive Polarity, Proceedings of the World Congress on Engineering , Vol III WCE 2012, July 4 - 6, London, U.K.
27. Hitoshi, O.; Teruo, N.; .Iwao, M. (2001) “Study of Micro Machining of Metals by EDM with High Frequency Vibration”, Takushima Prefectual Industrial Technology Center.
28. Ho, K., H., and Newman, S., T. (2003): State of the art electrical discharge machining (EDM), International Journal of Machine Tools and Manufacture, 43, pp. 1287-1300.
29. J.H. Zhang, T.C. Lee, W.S. Lau, X. Ai (1997): Spark erosion with ultrasonic frequency, Journal of Materials Processing Technology, 68, pp.83–88.
30. J.-P. Kruth, L. Stevens, L. Froyen, B. Lauwers (1995):Study of the white layer of a surface machined by die-sinking electro-discharge machining, CIRP Annals—Manufacturing Technology, 44, pp.169–172.
31. Jai Hindus.S , Prasanna Rajendra Kumar.R , Oppiliyappan.B & P.Kuppan (2013):Experimental Investigation on Electrical discharge machining of SS 316L, International Journal on Mechanical Engineering and Robotics, 1(2), pp.39-45.
32. Kansal H.K., Singh H., Kumar P. (2007):Effect of Silicon Powder Mixed EDM on Machining Rate of AISI D2 Die Steel, Journal of Manufacturing Processes, 9(1), pp.13-22.
33. Kansal H.K., Singh H., Kumar P. (2006): Performance parameters optimization (multi characteristics) of powder mixed Electric discharge Machining (PMEDM) Through Taguchi’s method utility concept, Indian journal of Engineering & material Science, 13, pp.209-216.
34. Ke Yu Shue, Yao Yang Tsai, Yo Ming Chang (2010): An Investigation of Attachment on Electrode Surface in dry edm, Publication: Advanced materials research Volume - Manufacturing Science and Engineering, 1, pp.407-412.
35. Klocke F., Lung D., Antonoglou G. and Thomaidis D. (2004): The effects of powder suspended dielectrics on the thermal influenced zone by electrodischarge machining with small discharge energies”, 14th Int. Symp. on Electromachining (ISEM XIV) J. Mater. Process. Technol. (Switzerland) (Edinburgh, Scotland, UK, 30 Mar-1 Apr 2004) Elsevier, 149, pp. 191-7.
36. Kuldeep Ojha, R. K. Garg,& K. K. Singh (2011):Parametric Optimization of PMEDM Process using Chromium Powder Mixed Dielectric and Triangular Shape Electrodes, Journal of Minerals & Materials

Characterization & Engineering, 10(11), pp.1087-1102.

37. Kunieda, M., Miyoshi, Y., Takaya, T., Nakajima, N., Bo, Y.Z., Yoshida, M., (2003): High speed 3D milling by dry EDM, CIRP Annals—Manufacturing Technology, 52, 147–150.
38. Kunieda, M., Muto, H., (2000): Development of multi-spark EDM, Ann. CIRP, 49 (1), pp.119–122.
39. Kunieda, M., Yoshida, M., (1997):Electrical discharge machining in gas, CIRP Annals – Manufacturing Technology, 46(1), pp. 143-146.
40. Kuo,C.L., Huang, J.D.(2004): Fabrication of series pattern micro disk electrode and its application in machining micro-slit of less than 10 μm, International journal of machine tools and manufacture, 44, pp.545-553.
41. L.Q. Li, W.S. Zhao, Z.L. Wang, B.Q. Kou, L.Y. Li. (2004):Discussion of electrical discharge machining in gas, The 31st IEEE International Conference on Plasma Science, ICOPS2004, ISBN: 0-7803-8334-6.
42. M Gostimirovic, P Kovac, B Skoric & M Sekulic (2012) "Effect of electrical pulse parameters on the machining performance in EDM", Indian journal of Engineering & Material Science, Vol. 18 pp. 411-415.
43. M. Ghoreishi, J. Atkinson, (2002) "A comparative experimental study of machining characteristics in vibratory", Journal of Materials Processing Technology 120, pp.374–384.
44. M. Kunieda, C. Furudate, High precision finish cutting by dry WEDM, CIRP Annals—Manufacturing Technology 50 (2001) 121–124.
45. M. Kunieda, S. Furuoya, N. Taniguchi, Improvement of EDM efficiency by supplying oxygen gas into gap, CIRP Annals—Manufacturing Technology 40 (1991) 215–218.
46. M. Kunieda, T. Takaya, S. Nakano. (2004): Improvement of dry EDM characteristics using piezoelectric actuator, CIRP Annals—Manufacturing Technology, 53, pp.183–186.
47. M. Kunieda, Y. Miyoshi, T. Takaya, N. Nakajima, Y.Z. Bo, M. Yoshida, (2003): High speed 3D milling by dry EDM, CIRP Annals—Manufacturing Technology, 52, 147–150.
48. M. Yoshida, M. Kunieda, (1999): Study on mechanism for minute tool electrode wear in dry EDM, Seimitsu Kogaku Kaishi/Journal of the Japan Society for Precision Engineering, 65, pp.689–693.
49. M.L. Jeswani,, (1981):Electrical discharge machining in distilled water, Wear , 72, pp.81–88.
50. Masahiro Fujiki & Jun Ni & Albert J. Shih (2011): Tool Path Planning for Near-Dry EDM Milling With Lead Angle on Curved Surfaces, Journal of Manufacturing Science and Engineering, 133, pp. 51005-1-51005-9.
51. Mathapathi U., Jeevraj S., Kumar S., Ramola I.C. (2013) "analysis of material removal rate with powder mixed dielectric", IJCAE, 4(3), pp. 316-332.
52. Ming Q.Y. and He L.Y. (1995): Powder-suspension dielectric fluid for EDM, Journal of Materials Processing Technology, 52(1), pp. 44-54.
53. Mohammadreza Shabgard1, Mirsadegh Seyedzavvar1 & Samad Nadimi Bavil Oliaei (2011): Influence of Input Parameters on the Characteristics of the EDM Process, Strojniški vestnik - Journal of Mechanical Engineering 57(9), pp.689-696.
54. Mohan, B.; Rajadurai, A.; Satyanarayana, K.G. (2004): Electric discharge machining of Al–Sic metal matrix composites using rotary tube electrode, Journal of Materials Processing Technology, 153–154, pp.978–985.
55. Muniu J.M., Ikua B. W., Nyaanga D.M. & Gicharu S. N. (2013): Study on Effects of Powder-Mixed Dielectric Fluids on Electrical Discharge Machining Processes", International Journal of Engineering Research & Technology, 2 (10), pp.2449-2456
56. Murti,V.S.; Philip,P.K.(1987): A Comparative Analysis of Machining Characteristics in Ultrasonic Assisted EDM by Response Surface Methodology, International Journal of Product Research, 25(2), pp.259–272.
57. N. Yoshiro, Y. Hisashi, (1993): Processing technologies and characteristics of wire-cut EDMs, Mitsubishi Electric Advance, 65, pp. 5–6.
58. N.Arunkumar, H.Shareef Abdur Rawoof, & R.Vivek (2012): Investigation on the Effect of Process Parameters for Machining of EN31 (Air Hardened Steel) By EDM, International Journal of Engineering Research and Applications, 2(4), pp.1111-1121.
59. Pandey, P., C., and Shan, H., S., (1980): Modern machining processes, University of Roorkee, New Delhe, Chapter 4, pp.84-113.

60. Pecas P. & Henriques E. (2003): Influence of silicon powder-mixed dielectric on conventional, pp. 1465–1471.
61. Prihandana, G.S.; Hamdi,M.; Wong,Y.S.;Kimiyuki,M.(2006):Effect of vibrated electrode in electrical discharge machining, Proceedings of the First International Conference and Seventh AUN/SEED-Net Field wise Seminar on Manufacturing and Material Processing, Kuala Lumpur, pp. 133–138.
62. Pushpendra S. Bharti, S. Maheshwari & C. Sharma (2012): Multi-objective optimization of electric-discharge machining process using controlled elitist NSGA-II, Journal of Mechanical Science and Technology, 26 (6), pp. 1875~1883.
63. Q.H. Zhang, J.H. Zhang, J.X. Deng, Y. Qin, Z.W. Niu, (2002): Ultrasonic vibration electrical discharge machining in gas, Journal of Materials Processing Technology, 129, pp.135–138.
64. Q.H. Zhang, J.H. Zhang, S.F. Ren, Z.W. Niu, X. Ai,(2005): A theoretical model of surface roughness in ultrasonic vibration assisted electrical discharge machining in gas, International Journal of Manufacturing Technology and Management,7, pp. 381–390.
65. Q.H. Zhang, R. Du, J.H. Zhang, Q. Zhang, (2005): An investigation of ultrasonic-assisted electrical discharge machining in gas”, International Journal of Machine Tools & Manufacture, DOI:10.1016/ j.ijmachtools.2005.09.023.
66. Q.H. Zhang, R.X. Du, J.H. Zhang, J.Y. Yang, S.F. Ren, (2004) : The mechanism of ultrasonic vibration improving MRR in UEDM in gas, Materials Science Forum, (471–472) pp. 741–745.
67. Reza Atefi, Ali Razmavar, Farhad Teimoori & Farshad Teimoori, (2012):The Investigation of EDM Parameters in Finishing Stage on Surface Quality Using Hybrid Model, Journal of Basic and Applied Scientific Research,.2(3), pp. 3061-3065.
68. S. Sharma, A. Kumar, N. Beri & D. Kumar (2010):Effect of aluminium powder addition in dielectric during electric discharge machining of hastelloy on machining performance using Reverse polarity, International Journal of Advanced Engineering Technology, 1(3), pp.13-24.
69. S. Tariq Jilani, P.C. Pandey, (1984):Experimental investigations into the performance of water as dielectric in EDM, International Journal of Machine Tool Design and Research, 24, pp.31–43.
70. S.H. Kang, D.E. Kim, :Effect of electrical discharge machining process on crack susceptibility of nickel based heat resistant alloy, Materials Science and Technology, 21, pp. 817–823.
71. S.H.Tomadi, M.A.Hassan, Z. Hamedon, Member, IAENG R.Daud, & A.G.Khalid (2009): Analysis of the Influence of EDM Parameters on Surface Quality, Material Removal Rate and Electrode Wear of Tungsten Carbide, Proceedings of the International Multi Conference of Engineers and Computer Scientists, Vol. II,Hong Kong, ISBN: 978-988-17012-7-5.
72. S.L. Chen, B.H. Yan, F.Y. Huang, (1999): Influence of kerosene and distilled water as dielectric on the electric discharge machining characteristics of Ti-6Al-4V, Journal of Materials Processing Technology, 87, pp.107–111.
73. S.Sivasankar & R.Jeyapaul (2013): Performance study of tool Materials and optimization of Process parameters during EDM on ZrB2-SiC composite through Particle swarm optimization Algorithm, International Journal of Engineering Science and Technology, 5(1), pp.133-159.
74. Sato,T.; Mizutani,T.; Yonemouchi,K.; Kawata,K.(1986): The development of an electro discharge machine for micro hole boring, Precision Engineering, 8, pp.163–168.
75. Shih, H.R.; Shu, K.M. (2007):A study of electrical discharge grinding using a rotary disk electrode, International Journal of advance manufacturing technology.
76. Singh P., Kumar A., Beri N. & Kumar V. (2010): some experimental investigation on aluminum powder mixed EDM on machining performance of hastelloy steel, International Journal of Advanced Engineering Technology, 11(2), pp.28-45.
77. Singh, S., Kansal, H.K., Kumar, P., (2005): Parametric optimization of powder mixed electrical discharge machining by response surface methodology, Journal of Materials Processing Technology, 169(3), pp.427– 436.
78. Singh, S., Kansal, H.K., Kumar, P. (2005): Parametric optimization of powder mixed electrical discharge machining by response surface methodology, Journal of Materials Processing Technology, 169 (3), 427– 436.
79. Soni, J.S.; Chakraverti, G. (1994): Machining characteristics of titanium with

rotary electro-discharge machining,Wear, 171, (1/2), pp.51–58.
80. Soni,J.S.; Chakraverti,G. (1997):Performance evaluation of rotary EDM by experimental design technique, Defense Science journal, 47(1), pp. 65-73.
81. Syed K. H. & Palaniyandi K. (2012): Performance of electrical discharge machining using aluminium powder suspended distilled water, Turkish J. Eng. Env. Sci., 36, pp.195 – 207.
82. T. Wang, J. Zhe, Y.Q. Zhang, Y.L. Li, & X.R. Wen (2013): Thermal and fluid field simulation of single pulse discharge in dry EDM, The Seventeenth CIRP Conference on Electro Physical and Chemical Machining (ISEM), Procedia CIRP,6 , pp. 427 – 431.
83. T. Wang, M. Kunieda, (2004): Dry WEDM for finish cut, Key Engineering Materials, (258–259), pp.562–566.
84. T. Wang, Y. Chen, M. Kunieda, (2003): Study on wire-cut electrical discharge machining in gas, Jixie Gongcheng Xuebao/Chinese Journal of Mechanical Engineering ,39, pp.76–80.
85. Tzeng Y.-F. and Chen F.-C. (2005): Investigation into some surface characteristics of electrical discharge machined SKD-11 using powder-suspension dielectric oil, Journal of Materials Processing Technology, 170(1-2) ,pp. 385-91.
86. Tzeng Y.-F. and Lee C.-Y. (2001): Effects of powder characteristics on electrodischarge machining efficiency., International Journal of Advanced Manufacturing Technology. 17(8) pp. 586-92.
87. Tzeng, Y.F., Lee, C.Y. (2001): Effects of powder characteristics on electro discharge machining efficiency, Int. J. Adv. Manuf. Technol., 17, 586–592.
88. Vishwakarma M., Khare K. & Parashar V., (2012): Response surface approach for optimization of Sinker Electric Discharge Machine process parameters on AISI 4140 alloy steel, International Journal of Engineering Research and Applications (IJERA), 2, pp.185-189.
89. W. Koenig, L. Joerres (1987): A aqueous solutions of organic compounds as dielectric for EDM sinking, CIRP Annals—Manufacturing Technology, 36, pp. 105–109.
90. W. Konig, F.-J. Siebers, (1993): Influence of the working medium on the removal process in EDM sinking, American Society of Mechanical Engineers, Production Engineering Division (Publication) PED 64, pp. 649–658.
91. W.S. Jhao, Q.G. Meng & Z.L. Wang (2002): The application on research on powder mixed EDM in rough machining, Journal of material processing Technology, 129, pp.30-33.
92. Wang, C.C., Yan, B.H., (2000): Blind hole drilling of Al2O3/6061Al composite uses rotary electro-discharge machining, Journal of Materials Processing Technology, 102, 90–102.
93. Wong, Y.S., Lim, L.C., Lee, L.C., (1995): Effect of flushing on electro-discharge machined surfaces, Journal of Materials Processing Technology 48, pp.299–305.
94. Wong, Y.S., Lim, L.C., Rahuman, I., Tee, W.M. (1998):Near-mirror-finish phenomenon in EDM using powder-mixed dielectric, Int. J. Adv. Manuf. Technol., 79, 30–40.
95. Xu, M.G.; Zhang, J.H.; Yule; Zhang, Q.H.; Ren, S.F., (2009):Material removal mechanisms of cemented carbides machined by ultrasonic vibration assisted EDM in gas medium, Journal of materials processing technology, 209, pp.1742–1746.
96. Y. Zhanbo, J. Takahashi, N. Nakajima, S. Sano, K. Karato, M. Kunieda, (2006): Feasibility of 3-D surface machining by dry EDM",(/ http://www.sodic.co.jptechimgarticle_s02.pdfS Downloaded on May 1 2013).
97. Y.S. Tarng, C.M. Tseng, L.K. Chung, (1997): A fuzzy pulse discriminating system for electrical discharge machining, Int. J. Mach. Tools Manuf., 37 (4), pp.511–522.
98. Yan,B.H.; Wang,C.C.; Liu,W.D.; Huang,F.Y.(2000): Machining Characteristics of Al2O3/6061Al Composite using Rotary EDM with a Disk like Electrode, International Journal of Advance Manufacturing Technology, 16, pp.322–333.
99. Yu, Z.B., Jun, T., Masanori K., (2004): Dry electrical discharge machining of cemented carbide, Journal of Materials Processing Technology, 149, 353–357.
100. Z.N. Guo, T.C. Lee, T.M. Yue, W.S. Lau, (1997): A study of ultrasonic aided wire electrical discharge machining, Journal of Materials Processing Technology 63, pp. 823–828.
101. Zhang, Q.H., Du, R., Zhang, J.H., Zhang, Q. (2006): An investigation of ultrasonic-assisted electrical discharge machining in gas, Int. J. Mach. Tools Manuf., 46, pp. 1582–1588.

102. Zhang, Q.H., Zhang, J.H., Deng, J.X., Qin, Y., Niu, Z.W. (2002): Ultrasonic vibration electrical discharge machining in gas, Journal of Materials Processing Technology, 129, pp.135–138.
103. Zhao, W.S., Meng, Q.G., Wang, Z. L. (2002): The application of research on powder mixed EDM in rough machining, Journal of materials processing technology, 129, pp.30–33.