EXPERIMENTAL INVESTIGATIONS INTO ELECTRO-DISCHARGE DRILLING OF Al_2O_3 USING ASSISTED ELECTRODE METHOD

By
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THESIS

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The foregoing thesis is hereby approved as a creditable study of an engineering subject carried out and presented in a manner of satisfactory to warrant its acceptance as a pre-requisite to the degree for which it has been submitted. It is understood that by this approval, the undersigned do not necessarily endorse or approve any statement made, opinion expressed and conclusion drawn therein but approve the thesis only for the purpose for which it has been submitted.

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1. INTRODUCTION

Nonconductive ceramics are composed of metallic and non-metallic elements. The covalent and ionic bonds of elements make these ceramics much stronger than metals. Nonconductive ceramics are also known as engineering ceramics or advanced ceramic materials. Due to the excellent chemical and physical properties, nonconductive ceramics have been using for many years in automotive spark plugs as an electrical insulator and high temperature resistant materials. Now these are also used in multifarious fabrication of domestic, industrial, building products and art objects. Examples include cutting tools, selflubricating bearings, turbine blades, internal combustion engines, heat exchangers, ballistic armour, ceramic composite automotive brakes, diesel particulate filters, a wide variety of prosthetic products, piezo-ceramic sensors etc . Currently, micro-parts made of engineering ceramics are used in biomedical field to fabricate femoral heads and acetabular cups for total hip replacement, dental implants and restorations, bone fillers and scaffolds for tissue engineering. Such a wide range of application makes ceramics as one of the most useful material in todays world. But one of the major problems is the machining of non-conductive ceramics, which is almost impossible with conventional machining processes because of its strength, brittleness, toughness, creep resistance, hardness etc. Hence, nonconventional machining such as chemical machining, abrasive water jet machining, ultrasonic machining, laser beam machining, electro discharge machining are used in processing of structures from nonconductive ceramic materials. EDM is one of the most established process compared to other non-conventional machining processes that can be used to machine the non- conductive ceramic materials using either ‘Assisting electrode method’ or ‘Doping ceramic method’. EDM is most popular because of its capability to machine hard materials and to produce complicated profiles and taking input energy less as compared to other non-conventional processes. Even highly delicate and fragile materials can be machined without any fear of distortion because there is no direct contact of tool and work piece. But its low efficiency and poor surface finish, subface and subsurface defects are the key problems which are needed to be solved for further development in machining efficiency by optimizing machining parameters.

In the present research work commonly used ceramic Alumina (Al_2O_3) has been machined using assisting electrode method, various parameters have been studied and and optimised based on the obtained results.

1.1. Need of Ceramic Materials

A ceramic is an inorganic non-metallic solid made up of either metal or non-metal compounds that have been shaped and then sintered by heating to high temperatures. In general, they are hard, corrosion-resistant and brittle. The extensively used best-known ceramics are pottery, glass, brick, porcelain, and cement. But the general definition of a ceramic is a nonmetallic and inorganic solid which is so broad that it covers a much wider range of materials. At one end of the scale, ceramics include simple materials such as graphite and diamond, made up from different crystalline arrangements of the element carbon. But at the other end of the scale, complex crystals of yttrium, barium, copper, and oxygen make up the advanced ceramics used in so-called high-temperature superconductors (materials with almost no electrical resistance). Most ceramics fall somewhere between these extremes. Many are metal oxides, crystalline compounds of a metal element and oxygen. Others are silicides, borides, carbides, and nitrides, respectively made from silicon, boron, carbon, and nitrogen. Some of the most advanced ceramic materials are combinations of ceramics and other materials known as cearmic matrix composites (CMCs).

Because of its excellent properties such as hardness, toughness, creep resistance ceramics have found their use in almost every aspect of life. So there is a strong demand of ceramics in different types of industries. Some of them are as follows:

(i) Automotive industry

In automobile industry ceramics are used in engine heat resistant parts like valve components. Ceramics also serve the purpose of backings in the crankshaft housing and components for water and fuel pumps. Ceramics made valve components is shown in the Fig.1.1

Fig.1.1. Valve and valve componenets made of ceramics

(ii) ***Equipment and mechanical engineering***

High wear resistance, temperature resistance and corrosion resistance make ceramic safer than other materials in equipment and mechanical use. They are also used in cutting tools and pumps.

(iii) ***Electronics industry***

In electronics industry ceramic heat sinks provide the right climate for high power electronics. Ceramics are also used in capacitors and insulators as shown in the Fig.1.2

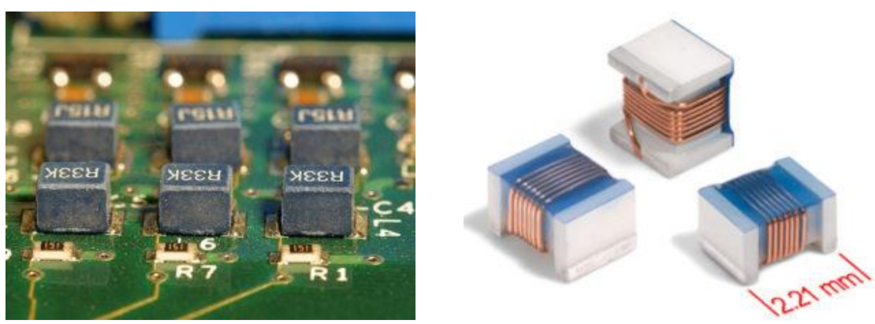

Fig.1.2. Capacitors and inductors

(iv) Medical field

Biocompatible and wear- resistant ceramics enable doctors to provide patient with optimum care and help patients master the challenges of everyday life again. Ceramics are used in artificial bones, in dentures and medical implants as shown in the below Fig.1.3

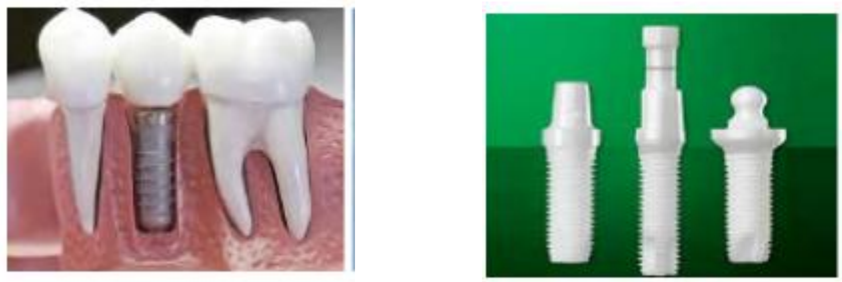

Fig.1.3. Ceramics in dentistry and medical implants

(v) Energy and environment

Ceramic matrials help safe, low wear process control. They reduce emissions and ensure efficient use of resources in many area of energy supply and environmental technology for ex- water treatment and recycling of waste.

Ceramic materials ensure long life of parts subjected to high stress during conveying,transport or the processing of raw materials. Ceramic materials can also withstand extreme temperatures and mechanical stresses in applications for generating energy in power plant engines and turbines or in system of photovoltaic, solar thermal energy conversion etc.

(vi) Aerospace industry

In aerospace industry ceramics serve the purpose of sheilding a hot running airplane engine from damaging other components. They are also used as a high-stress, high temperature and lightweight bearing and structural components. Missile nose-cones are made of ceramics and shielding of the missile internals from heat is also done with the help of ceramics. Space shuttle tiles and rocket nozzles are also made of advanced ceramics. Fig.1.4 shows the application of ceramics in aerospace industry.

Fig1.4. Aircraft engines and braked made of ceramics

(vii) Ceramic in mordern industry

Zirconium oxide ceramics are used in the manufacturing of knives. Its blades stays sharp for much long as compared to steel knives. Ceramics such as alumina, boron carbide and silicon carbide are used in bullet-proof vests. Ceramics such as silicon nitride are used in ball bearings. Their higher hardness ensures less susceptibility to war and can offer more than triple lifetime. Also high-tech ceramics are used in watch making to produce watch cases. The material is valued by watch makers for its light weight, scratch resistance, durability and smooth touch.

1.2. Types of Ceramic Materials

According to Luis et al [1] the term ceramic or advanced ceramic is applied to a range of materials generally obtained from inorganic primary materials with a high grade of purity. These ceramics are classified into oxide ceramics (Al_2O_3, ZrO_2 etc.) and non-oxide ceramics (Si_3N_4, SiC etc.). But as far as manufacturing and uses are concerned ceramics can be classified in a broarder category as shown in Fig.1.5 below

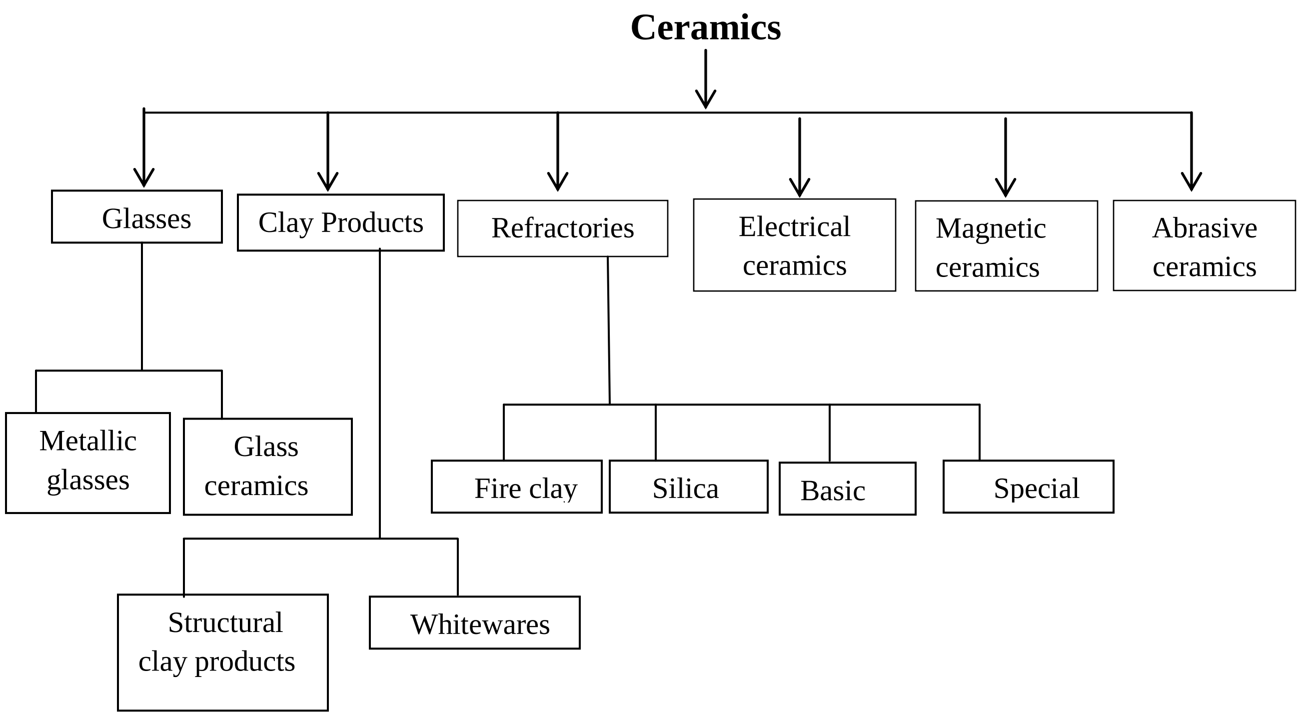

Fig.1.5. Classification of ceramic materials on the basis of application.

Classification of ceramics are as follows:

(i) Glasses

Glass materials are generally transparent and very brittle (when not heat treated). The transparency is a result of the lack of grain boundaries and pores in the structure of the glass. This lack of grain boundaries also leads to the brittleness, as cracks can propagate unhindered.

(ii) Clay products

Many common ceramics such as bricks and tiles are based primarily on clay. These are pressed or extruded into shape while in a wet plastic state and then dried and fired. Higher density clay products exhibit better mechanical properties but at the same time have worse insulating properties.Increased vitrification leads to higher densities and is achieved through finer original particle size and increased firing temperature.

(iii) Refractories

Because of their high heat resistance, ceramic materials are used as refractories. Refractory ceramics are insulating materials and are designed to withstand high stresses and temperatures and must also resist the effects of molten metals, abrasive particles and hot gases. Ceramics made of pure oxides are quite often the best refractories, however, these are expensive and therefore mixtures of ceramic compounds are often used.

(iv) Electrical Ceramics

Ceramics can display a variety of useful electrical and magnetic properties. Some ceramics are good conductors such as graphite while some have high resistivity such as SiC which is used in heating elements. Unlike in metals, the conductivity of ceramics increases as temperature increases. This is because conduction is based on the movement of anions and cations. Mobility of the ions is only possible when there is enough thermal heating to supply sufficient energy.

(v) Magnetic Ceramics

Magnetic ceramics are divided into two categories – traditional low conductivity magnets and superconducting magnets.

Low conductivity magnets are used in applications where the magnet is required to have some electrical insulating properties, such as in transformers.

Superconducting magnets are a special class of ceramics that are able to conduct electricity with no resistance and therefore no energy loss. This special property is limited, however, as it is only possible below a critical magnetic field and a critical temperature, T_C, which is always very cold.

(vi) Abrasive Ceramics

Abrasive ceramics are used to grind or cut away other softer material. Primarily, when considering the design of a abrasive material it is hardness and wear resistance that are of the most importance. Toughness is also considered as a necessary requirement so that the abrasive material does not shatter during grinding.Abrasives can be either natural or synthetic. Common examples include diamond, silicon carbide SiC, tungsten carbide WC, or normal silica sand.

1.3. Applications of Ceramic Materials In Industries

Ceramics are used in many industrial applications to support manufacturing within sectors such as metallurgical, chemical, mechanical, and energy production.

Properties that make these materials desirable in these fields are primarily wear and corrosion resistance, hardness, resistance to chemical attack, thermal and electrical insulation, and high-temperature resistance and compressive strength.

Some of the most common applications of ceramics in manufacturing industries are enlisted below:

(i) The largest category of products is represented by refractories. By definition, refractories are materials that are capable of withstanding operating conditions of 1,000°C or greater. Although approximately 80% of the refractory market is accounted for by the metallurgical sector (for processing of both ferrous and non-ferrous metals), these products also find application in other industries such as glass, ceramics and cement manufacturing, as well as in power generation.

(ii) In the iron and steel industry, refractories are used as linings for metal melting furnaces, for the ladles that hold, transport, and pour the molten metal, and for the pipes that carry away hot gases. Other items needed to handle the molten metals, such as hooks and sleeves, are also made of refractory materials. In other industries, refractories are mainly employed to build kilns, furnaces, kiln furniture, and vessels for material processing (e.g., sintering, melting, crystallization, and high-temperature chemical reactions).

(iii) Catalysts and catalyst carriers (i.e., substrates and media that support the catalyst) represent another relevant group of ceramic products for industrial applications. They are primarily used in petroleum refining and chemical processing for manufacturing fuels, polymers, bulk chemicals, and pharmaceuticals that would not be possible otherwise, as well as for reducing environmental pollution.

(iv) Ceramics are also important for filtration and separation processes. Products consist of membranes, macrofiltration media, and filters, the difference among the three being that membranes have very small pore sizes (below 10 microns); macrofiltration media have pore sizes between 10 microns and 1,000 microns; and filters have larger openings. Membranes are often made from ceramic nanofibers. Ceramic separation media are less common and more expensive than polymeric media, but are favored for the treatment of high temperature and/or corrosive fluids. They also offer the advantage of being less affected by fouling and can be more easily regenerated with steam and heat treatments. The higher initial cost is compensated by a longer lifetime and reduced downtime.

(v) Many wear and corrosion resistant parts and coatings find application in manufacturing. They include products such as ceramic cutting tools, bearings, pump seals, nozzles, valves, and thread guides for the textile sector. The chemical and petrochemical industry relies on ceramic matrix composites for the fabrication of pipes, pumps for abrasive fluids, and liners for gasifying systems.

(vi) Abrasive ceramics are common for polishing, grinding, and finishing operations and to manufacture parts with very tight tolerances. They are sold as powders, grains, beads, and wheels.

(vii) In addition, ceramics are also used in industrial applications including thermal barrier coatings and thermal insulating textiles, and electrical insulators for machinery components and sensors.

1.4. Machining of Ceramic Materials by Various Machining Processes

The last two decades have seen an enormous surge in interest in ceramic materials and, as a result there have been significant advances in their development and usage. It is appreciated that there are characteristics of these materials that are particularly useful, including very high hardness and wear resistance and high specific strength, but it is the retention of these properties at elevated temperatures that present ceramic materials as a generic group as potentially unique solutions to a number of engineering application problems. Composite ceramics are being developed to address the well-documented problems of brittle nature and low fracture toughness; reinforcing phases e.g. particulate, whisker or continuous fibre introduce mechanisms such as crack deflection, crack blunting or load transfer.

Most traditional machining techniques are generally precluded, and the cost of producing component shapes is often extremely high as it usually involves the use of expensive and time consuming diamond grinding. Unfortunately, whilst aiding some aspects of the material behaviour, a composite structure can compound the problems of machining. Thus, the single greatest obstacle to the full realisation of the potential of ceramics is the development of a cost-effective machining method that does not significantly reduce the beneficial material properties of the processed surface.

The methods developed for ceramics machining are:

(i) Machining of ceramics in the presintered state

Sintered ceramics are very hard and therefore their machining is an expensive, difficult and time consuming process.Ceramic parts may be effectively machined before the final sintering stage either in the “green” i.e. non-sintered powder compact state or in the presintered “bisque” state. Conventional machining methods (milling, drilling, turning) may be applied for the ceramic parts in the presintered state.Titanium nitride (TiN) coated high speed steel tools, tungsten carbide tools and polycrystalline diamond (PCD) tools are used in machining of presintered ceramics.

(ii) Grinding Techniques

Grinding is the most widely used method of machining of Ceramics in the sintered state.Grinding operation involves a rotating abrasive wheel removing the material from the surface of the workpiece. The grinding zone is continuously flushed with a fluid coolant, which cools the grinding zone, lubricates the contact between the wheel and the part surfaces, removes the micro-chips (debris) produced in the grinding process. Resin-bond wheels with either synthetic or natural diamond of different grit size pressed at different concentrations in polymer (resin) matrices are commonly used for grinding ceramics.

(iii) Ultrasonic machining of ceramics

Ultrasonic machining (UM) of ceramics is the machining method using the action of a slurry containing abrasive particles flowing between the workpiece and a tool vibrating at an ultrasonic frequency.

The vibration frequency is 19 ~ 25 kHz.

The amplitude of vibration 0.0005 - 0.002" (13 – 50 μm).

During the operation the tool is pressed to the workpiece at a constant load.

As the tool vibrates, the abrasive particles or grits dispersed in the slurry strike the ceramic workpiece and remove small ceramic debris fracturing from the surface by brittle fracture.

(iv) Rotary ultrasonic machining of ceramics

Rotary ultrasonic machining (RUM) of ceramics combines grinding operation with the method of ultrasonic machining. A core drill tool made of a metal bonded diamond grits is used in the rotary ultrasonic machining (commonly drilling).The tool is rotating and simultaneously vibrating at an ultrasonic frequency. The tool is continuously fed and pressed at a load towards the ceramic workpiece causing abrasive action performed by the rotating-vibrating diamond grits.A fluid coolant is continuously flowing through the core of the tool to the grinding zone cooling it and removing the debris produced in the grinding process. Rotary ultrasonic machining is much more effective than conventional ultrasonic machining. The RUM material removal rate is up to 492 mm^3/min.

(v) Laser assisted machining of ceramics

Laser assisted machining (LAM) is the method of machining ceramics using a laser beam directed to the workpiece area located directly in front of the conventional cutting tool. The laser beam heats and softens (not melts) the ceramic material at the surface just prior the cutting action.As a result the cut material becomes ductile and it may be removed much faster than in conventional cutting operation without a laser assistance. Titanium nitride coated tools are used for the laser assisted machining of ceramics.

(vi) Electro chemical discharge machining (ECDM) of ceramics

Electro Chemical Discharge Machining (ECDM) process has combined characteristic of ECM and EDM that enables it to machine electrically conductive materials at a rate five to fifty times higher than ECM & EDM irrespective of the typical properties of newer materials such as chemical inertness and high strength high temperature resistance (HSHTR) by electro chemical dissolution (ECD) and by electric discharge erosion (EDE) simultaneously. The novelty of this process is that electrically non conductive HSHTR materials that are difficult to machine by conventional methods can also be machined by this process. Somehow, this process itself imposes certain limitations such as low machining efficiency, heat affected zone, radial overcut etc. especially while machining some of the electrically non conductive materials.

1.5. Problems Arise During Machining of Ceramics

Ceramics like Alumina (Al_2O_3), Silicon Carbide (SiC), Zirconia (ZrO_2) and Silicon nitride (Si_3N_4) have the special properties of high hardness which is maintained at elevated temperatures encountered in machining/grinding and have good wear resistance, corrosion resistance and chemical stability. However, machining of ceramics, maintaining desired surface finish and surface integrity, is a challenging task due to their very high strength and low fracture toughness. Use of conventional coolants is also not possible due to their low thermal conductivity and the thermal shock created by application of low temperature coolant at a localized area. Moreover ceramic machining using conventional techniques is also not possible because of it’s hardness and wear resistance properties. In non-conventional machining laser and ultrasonic machining have been used to machine ceramics, but because of low material removal rate, high tool wear and poor surface finish we have to look forward for some other technique to be used to machine ceramics, which could be feasible.

To overcome the above mentioned problems in ceramics, ceramic matrix composites are developed by providing reinforcements in the form of whiskers, small particles or powder of materials like Carbon, SiC, TiC. The reinforcements improve the toughness and, in some cases, make the material thermally and electrically conductive. The advantages of a conductive ceramic based composite material include an option to machine by Electric Discharge Machining (EDM) and also to use coolant while machining to improve surface quality. Due to the improved toughness and improved thermal conductivity, the detrimental effect of coolant causing surface and subsurface cracks is obviated. The main negative aspect of these materials is that they are very difficult to machine due to their high hardness and strength, which restricts their industrial exploitation. The only options for machining / grinding these materials are by a CBN (Cubic Boron Nitride) or a diamond abrasive grinding wheel.

Since these materials are used in high technology applications, the components manufactured from them usually require good dimensional control and surface finish. Hence, in almost all applications, some finishing operation is required which is usually the grinding. The major issues involved in grinding of ceramics and ceramic matrix composites (CMC) are high tangential and normal cutting forces, grinding temperature, surface roughness, surface cracks and subsurface damages, A combination of optimum values of these response parameters are sought while maintaining a good material removal rate (MRR). Grinding costs involved are also to be addressed as, to avoid high tool wear, abrasives like CBN and diamonds are used.

1.6. Prospects of EDM Process for Machining of Ceramics

Today ceramics are used in many industrial applications, for example, in the biomedical field, for high-temperature components or for cutting tools. This is attributed to their excellent mechanical and physical properties, as low density, high strength, and hardness or chemical resistance. However, these specific mechanical properties lead to problems regarding the postprocessing of ceramics. In particular, machining processes require expensive tools which cause high manufacturing costs to machine ceramics. Consequently, there is a demand for alternative machining processes. Electrical discharge machining (EDM) is a thermal ablation process which is based on electrical discharges between a tool and a workpiece. The advantages of EDM are more in focus for ceramic machining. These advantages include

(i) The process of being a noncontact technology, an independency of material brittleness and hardness, a low impact on the material, and the achievable microstructures.

(ii) There is no physical contiguity of cathode (tool) and anode (workpiece) thus mechanical chatter and trembling problem can be eliminated in machining.

(iii) Material irrespective of their hardness, brittleness softness and fragileness can be machined by EDM. EDM has the ability to machine miniaturized machined parts of metal, metallic alloy, graphite, and ceramics irrespective of the hardness and brittleness.

(iv) EDM successfully machined intricate shapes efficiently and precisely irrespective of the dimensions and material of the product.

(v) As compared to other non traditional machining processes which are used for machining of ceramics, EDM is the most cost effective process for machining of ceramics.

(vi) Surface quality obtained after machining is much better as compared to other machining processes such as ultrasonic machining, laser machining, abrasive jet machining etc.

Considering the above advantages of Electro discharge machining we can conclude that it is one of the most efficient and feasible process of machining ceramics as compared to other non-traditional machining processes.

1.7. Fundamentals of EDM Process

EDM is the process of removing material generally from a conductive work piece by applying a high-frequency pulsed, electrical current to it via a solid, shaped electrode or wire. The electrode never touches the work piece but instead discharges its current through an insulating dielectric fluid (water or oil) across a very small spark gap depending upon voltage, amperage, electrode material and dielectric type. The spark is plasma hot, reported to be in the range of 8000-12000ºC, which melts and vaporises the work piece material. The EDM process is used when the work piece material is too hard, or when the shape or location of the detail cannot easily be conventionally machined. This makes many formerly difficult projects more practical, and many times it can be the only feasible way to machine a part, shape or material. The mechanism of material removal rate is shown in Fig.1.6

Electric discharge machining works on the principle of spark generation and metal is removed due to spark erosion and thermal energy of spark. Both tool and the workpiece should be electrically conductive and a potential difference is being applied between them under dielectric medium generally kerosene or ionized water. A minimal gap is maintained between tool electrode and workpiece. Depending upon the applied potential difference and gap, an electric field is generated and sparks produce resulting into the spark erosion of work material.

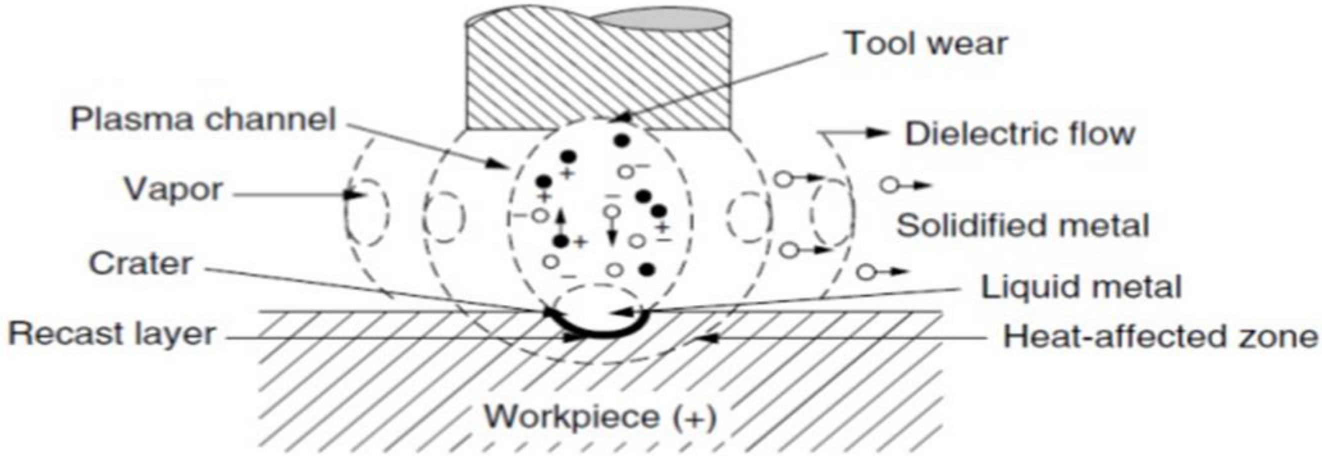

Fig.1.6. Mechanism of material removal in EDM [2]

EDM is a thermo-electrical material removal process, in which the tool electrode shape will reproduce into the work material. The EDM system consists of several subsystems e.g. a machine tool system, power supply system, control and delivery system. The machine tool holds the shaped electrode and advances into the work material and produces high frequency series of electric spark. Tool electrode and work material are separated with the gap of about 0.01-0.5mm having dielectric fluid between them. A series of voltage is applied around the tool and workpiece in range of 20-120V resulting in electric breakdown in radius of around 10µm.

Generally, the workpiece is connected to the positive terminal of the power supply and the tool is connected to negative terminal. As soon as the electric field is established between the workpiece and the tool, free electrons on the tool are subjected to electrostatic forces. If the bonding energy work function of the electrons is less, electrons are emitted from the tool which is connected to the negative terminal. Such emission of electrons is termed as cold emission. Through the dielectric medium “cold emitted” electrons are then accelerated towards the job. There would be collisions between the electrons and dielectric molecules as they gain velocity and energy, and start moving towards the job, such collision results in ionization of the dielectric molecule depending upon the work function of the dielectric molecule and the energy of the electron. Thus, as the electrons get accelerated, more positive ions and electrons would get generated due to collisions. At the spark gap, this cyclic process would increase the concentration of electrons and ions in the dielectric medium between the tool and the job. The matter existing in the channel is characterized as "plasma" as its concentration is too high. The electrical resistance of such plasma channel would be very less. Thus, all of a sudden, a large number of electrons will flow from the tool to the workpiece and ions from the workpiece to the tool which is called avalanche motion of electrons. Such movement of electrons and ions can be visually seen as a spark. Thus, the electrical energy is dissipated as the thermal energy of the spark. The high-speed electrons then impinge on the work material and ions on the tool electrode. The kinetic energy of the electrons and ions on impact with the surface of the workpiece and tool respectively would be converted into thermal energy or heat flux. Such intense localized heat flux leads to extreme instantaneous confined rise in temperature which would be in excess of 10,000 ºC. Such extreme rise in localized temperature leads to material removal by ablation. Material removal occurs due to instant vaporization of the material as well as due to melting. The molten metal is not removed completely but only partially. As the potential difference is withdrawn. The plasma channel is no longer sustained. As the plasma channel collapse, it generates pressure or shock waves, which evacuates the molten material forming a crater of removed material around the site of the spark. A schematic diagram of EDM setup is shown in Fig.1.7

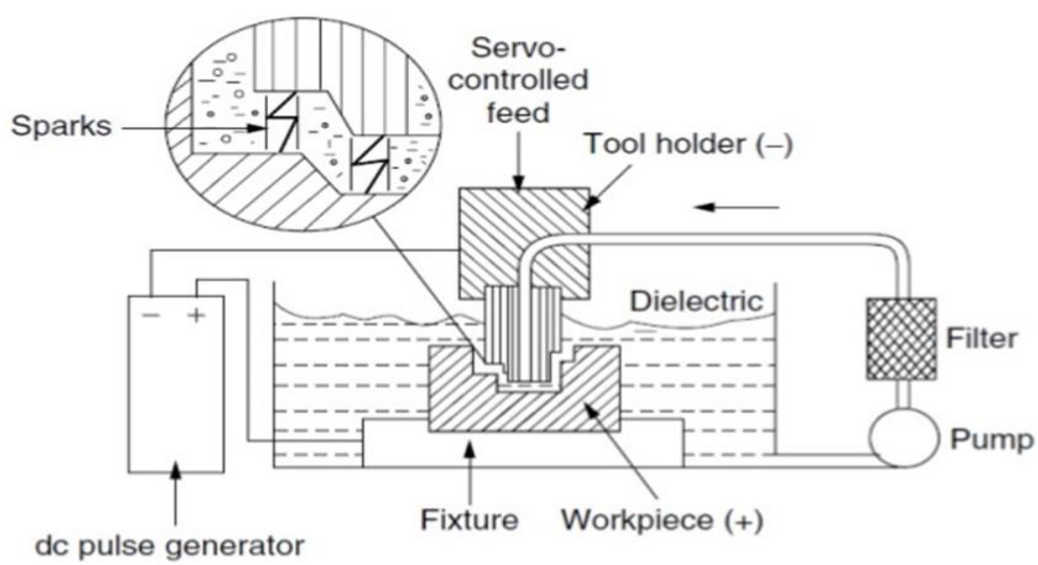

Fig.1.7. Electro Discharge Machining setup [3]

Thus to summarize, the material removal in EDM mainly occurs due to formation of shock waves as the plasma channel collapse owing to discontinuation of applied potential difference. Generally, the workpiece is made positive and the tool negative. Hence, the electrons strike the job leading to crater formation due to high temperature and melting and material removal. Similarly, the positive ions impinge on the tool leading to tool wear. In EDM, the generator is used to apply voltage pulses between the tool and the job. A constant voltage is not applied. Arcing leads to localized material removal at a particular point whereas sparks get distributed all over the tool surface leading to uniformly distributed material removal under the tool.

1.8. Literature Survey of The Past Research Works

As EDM has various problematic areas which have already been discussed in pevious chapter. Many researchers and manufacturing engineers are trying to overcome this problems so that EDM processes can be used successfully in modern manufacturing industries. But the material removal mechanism and the effects of various process parameters of EDM process are still unclear. Therefore, to exploit full potential of EDM in manufacturing domain, research still needs to improve its accuracy and compactness. The survey of past research investigations from different engineers and researchers have been documented as follows:

Sabur *et al.* [4] investigated that machining of non conductive ceramic materials was difficult and most of the unconventional techniques were not applicable because of their high brittleness. In this study, experiments were done to investigate the effect of input power on the material removal rate (MRR) and to explore the material removal mechanism. Electro discharge machining (EDM) technique, a noncontact machining process, was applied for processing nonconductive ceramic ZrO_2 using assisting electrode. In this technique, pyrolytic carbon layer on the ceramic surface formed by the cracked carbon from the carbonic dielectric, played the key role for continuous EDM. The formation of pyrolytic carbon and its stability was depended upon the input power, workpiece material, tool electrode material, dielectric substance, polarity, and discharge duration.. The experimental results showed that the material was removed in EDM of nonconductive ZrO_2 ceramic mostly by spalling and it increased with the increase of input power.

Lee T.C. and Lau W.S. [5] investigated the mechanisms behind the EDM machining of conductive composlte ceramic and to correlate the various properties with this removal process. Firstly, the energy required to remove the high melting temperature material by melting and evaporation and to overcome the high electrical resistance was much higher. Secondly, thermal stress failure mostly occurred in these materials because of their poor thermal conductivity. Lastly, the pulse frequency was restricted by the high electrical resistance of the material. Further investigation suggested that the material removal process in ceramics not only consisted of melting and evaporation as in case of conductive materials but also other mechanisms were involved such as thermal spalling.

Mohri *et al.* [6] studied that insulating ceramics can be easily machined using assisting electode method. The paper dealt with a new method of machining insulating ceramics by EDM. In this method, a metal plate or metal mesh was arranged on the surface of ceramic insulator as an assisting electrode. The ceramics can be machined very easily with a copper electrode in sinking EDM or with brass wire elecfrode in WEDM using kerosene as working fluid. Electrical conductive compounds involving cracked carbon from working oil were generated on the surface of the ceramics. It maintained electrical conductivity on the surface of the work piece during the machining. Some examples of machined products with this method were presented. The mechanism of' the machining of insulating ceramics was discussed with the principle in the surface modification technique by EDM which had been developed in recent years.

Schubert *et al.* [7] discussed the various industrial applications of ceramic materials which is attributed because of their excellent mechanical and physical properties such as low density, high strength and hardness or chemical resistance. However these specific mechanical properties lead to problem regarding the postprocessing of ceramics. The cutting process required expensive tools eventually leading to high manufacturing costs. So they stated that there was a demand for alternative machining process of ceramics. Microelectrical discharge machining (micro-EDM) is a thermal abration process which is based on electrical discharges between the tool and the workpiece. The advantages of micro-edm were more and more in focus of ceramic machining. These advantages included the process of being a non contact technology, an independency of material brttleness and hardness, a low impact on materials and an achievable micro-structures. So this paper presented the current state of investigations regarding mico-EDM of ceramics. Beside the process principle of EDM, the used procedures for machining ceramics and insulating ceramics were also described. Furthermore several examples were also demonstrated to study the possibilities of micro-EDM regarding machining of ceramics.

Abbas *et al.* [8] discussed the current research trends in electrical discharge machining. This paper reviewed the research trends in EDM on ultrasonic vibration, dry EDM machining, EDM with powder additives, EDM in water and modeling technique in predicting EDM performances. The review of the research trends in EDM on ultrasonic vibration, dry EDM machining, EDM with powder additives, EDM in water and modeling technique in predicting EDM performances was presented. In each topic, the development of the methods for the last 25 years had been discussed. The progress of development in each area was presented using charts. The ultrasonic vibration method suitable for micro machining, dry machining was cost effective, EDM in water was introduced for safe and conducive working environment, EDM with powder additives was concerned more on increasing SQ, MRR and tool wear using dielectric oil and EDM modeling was introduced to predict the output parameters which leads towards the development of precise and accurate EDM performance. For each and every method introduced and employed in EDM process, the objectives were the same: to enhance the capability of machining performance, to get better output product, to develop technique to machine new materials and to have better working conditions.

Hanaoka *et al.* [9] performed die sinking EDM on three ZrO_2-Y_2O_3 ceramics containing varying amounts of Al_2O_3. Three types of insulating ZrO2 ceramics were sintered and machined using sinking EDM in order to investigate the effects of different additive amounts on the machining properties of ZrO_2-Y_2O_3 insulating ceramics. The material removal rate, wear ratio of the electrode, and the surface roughness were estimated. As the experimental factors, the ideal polarity of the electrode, setup discharge current, and

Al_2O_3 additive amount were researched. The electrically conductive layer adhesion condition was recorded by SEM observation.

Petrofes and Gadalla [10] investigated that Increasing material removal rate (MRR) and minimizing recast layer hardness are critical issues in machining non-conductive ceramic using micro-electro discharge machining (micro-EDM).The two main parts of this research were process development and the analysis of MRR and recast layer hardness. In process development, the appropriate use of assisting electrode (AE), polarity, flushing, feed rate, gap voltage, and tool electrode rotational speed are identified. The better machinability of ZrO_2 was found to be with copper adhesive as AE, positive work-piece polarity, 3-μm/s feed rate, and work-piece submerged in dielectric fluid with one-way circulation. Empirical models were developed for the estimation of MRR and recast layer hardness. The optimum parameters for maximum MRR and minimum recast layer hardness were found to be at a 370-rpm rotational speed and at 80-V gap voltage.

Mohri *et al.* [11] investigated that micro-electrical discharge machining (micro-EDM) is a thermal abrasion process which is based on electrical discharges between a tool and a work-piece. The advantages of micro-EDM are more and more in focus for ceramic machining. These advantages include the process of being a noncontact technology, an independency of material brittleness and hardness, a low impact on the material, and the achievable micro structures. The current state of investigations regarding micro-EDM of ceramics had been presented in this paper. Beside the process principle of EDM, the used procedures for machining ceramics and insulating ceramics were described. Furthermore several machining examples were presented to demonstrate the possibilities of the micro-EDM process with regard to the machining of ceramics.

Kalajahi *et al.* [12] developed a thermal modeling and finite element simulation of electrical discharge machining (EDM), taking into account several important aspects such as temperature-dependent material properties, shape and size of the heated zone (Gaussian heat distribution), energy distribution factor, plasma flushing efficiency, and phase change to predict thermal behavior and material removal mechanism in EDM process. Temperature distribution on the cathode was calculated using ANSYS finite element code, and the effect of EDM parameters on heat distribution along the radius and depth of the workpiece was obtained. Temperature profiles were used to calculate theoretical material removal rate (MRR) from the cathode. Theoretically calculated MRRs were compared with the experimental results, making it possible to precisely determine the portion of energy that entered the cathode for AISI H13 tool steel. Also in this paper, the effect of EDM parameters on MRR was investigated by using the technique of design of experiments and response surface methodology. Finally, a quadratic polynomial regression model was proposed for MRR, and the accuracy of this model had been checked by means of analysis of residuals.

Mohri *et al.* [13] investigated that machining operations for fabricating structures from nonconductive ceramic materials are difficult and most of the traditional machining techniques are not applicable because of its high brittleness. Electro discharge machining (EDM) technique, a noncontact machining process, is applied for processing nonconductive ceramic using assisting electrode. In this technique, pyrolytic carbon layer on the ceramic surface formed by the cracked carbon from the carbonic dielectric, plays the key role for continuous EDM. The formation of pyrolytic carbon and its stability depends upon the input power, work-piece material, tool electrode material, dielectric substance, polarity, and discharge duration. In this study, experiments were done to investigate the effect of input power on the material removal rate (MRR) and to explore the material removal mechanism. The experimental results show that the material is removed in EDM of nonconductive ceramic mostly by spalling and it increases with the increase of input.

Vishwakarma *et al.* [14] documented the FEA modelling of material removal rate in electrical discharge machining of Al6063/SiC composites. Material removal rate (MRR) modeling has been carried out using an axisymmetric model of Al-SiC composite during electrical discharge machining (EDM). A FEA model of single spark EDM was developed to calculate the temperature distribution.Further, single spark model was extended to simulate the second discharge. For multi-discharge machining material removal was calculated by calculating the number of pulses. Validation of model has been done by comparing the experimental results obtained under the same process parameters with the analytical results. A good agreement was found between the experimental results and the theoretical value.

Ho KH and Newman [15] investigated that electrical discharge machining (EDM) was a well-established machining option for manufacturing geometrically complex or hard material parts that were extremely difficult-to-machine by conventional machining processes. The paper reviewed the research work carried out from the inception to the development of die-sinking EDM within the past decade. It reported on the EDM research relating to improving performance measures, optimizing the process variables, monitoring and control the sparking process, simplifying the electrode design and manufacture. A range of EDM applications were highlighted together with the development of hybrid machining processes. The final part of the paper discussed these developments and outlined the trends for future EDM research.

Lauwers *et al.* [16] investigated the manufacturability of B_4C, SiC, Si_3N_4-TiN by milling EDM and compared the performance of it to conventional sinking EDM. It was shown that due to the good flushing conditions, milling EDM performs well, even for the machining of ceramic materials with a rather low electrical conductivity (B_4C, SiC). Because the used milling EDM technique removed material in a layer by layer fashion (2D-machining), a new strategy for the machining of complex 3D-shapes in ceramic material was developed. It consisted of a milling EDM pre-machining step, followed by one or more finishing sinking EDM steps. The developed strategy was validated on an industrial example and compared to a pure sinking EDM strategy. Time reductions of more than 50% were obtained.

Schubert and Zeidler [17] investigated the applicability of micro-EDM for the machining of nonconductive ceramics. Tests were undertaken using micro–EDM drilling with Tungsten carbide tool electrodes and ZrO_2 ceramic work-pieces. A starting layer, in literature often referred to as 'assisting electrode' was used to set up a closed electric circuit to start the EDM process. Combining carbon hydride based dielectric and a specially designed low-frequency vibration setup to excite the work-piece, the process environment could be held within parameters to allow for a constant EDM process even after the starting layer was machined. Tungsten carbide tool electrode and Y_2O_3- and

MgO- stabilized ZrO_2 work-pieces were used. The current and voltage signals of the discharges within the different stages of the process (machining of the starting layer, machining of the base material, transition stage) were recorded and their characteristics compared to discharges in metallic material. Additionally, the electrode feed was monitored. The influences of the process parameters were analysed with regard to the discharge type, electrode wear and process speed.

Fukuzawa *et al.* [18] investigated that the insulating ceramics were processed with sinking and wire cut electrical discharge machining (EDM). The new technology was named as the assisting electrode method. In the machining, the electrical conductive material was adhered on the surface of insulating work-piece as the starting point of electrical discharge. As the processing operated in oil, the electrical conductive product composed of decomposition carbon element from working oil adhered on the work-piece during discharge. The discharges generated continuously with the formation of the electrical conductive layer. So, the insulating ceramics turn to the machinable material by EDM. They introduced the mechanism and the application of the machining of insulating ceramics such as $Si_3N_4$and ZrO_2.

Pandey and Singh [19] investigated EDM as a process that involved a controlled erosion of electrically conductive materials by the initiation of rapid and repetitive spark discharges between the tool and work-piece separated by a small gap of about 0.01 to 0.50. This gap was either flooded or immersed in a dielectric fluid. The controlled pulsing of direct current between the tool and the work piece produceed the spark discharge. The EDM process that we know today is a result of various researches carried out over the years. EDM researchers explored a number of ways to improve the sparking efficiency with various experimental concepts. Despite a range of different approaches, every new research shareed the same objectives of achieving high metal removal rate with reduction in tool wear and improved surface quality. This paper reviewed the vast array of research work carried out within past decades for the development of EDM. This study mainly focused on aspects related to surface quality and metal removal rate which are the most important parameters from the point of view of selecting the optimum condition of processes as well as economical aspects.

Chandramouli S *et al.* [20] investigation showed that current, pulse on time and pulse off time have significant effect on MRR, TWR and SR. The MRR was increasing with increase in current and decrease initially with increase in the pulse on time and increase later with an increase in pulse on time. MRR was increasing with increase in the pulse off time but the increase was less as compared to pulse on time. TWR was increasing linearly with increase in the current. The TWR was decreasing with increase in pulse on time, when increase in pulse off time the TWR was increasing. The SR was increasing with increase in current and pulse on time but decreasing with increase in pulse off time.

T Rajmohan *et al.* [21] examined the effect of electrical discharge machining parameters such as pulse on time, pulse off time, voltage and current on MRR in 304 stainless steel by means of Taguchi method. It was found that different groupings of EDM process parameters were essential to achieve higher MRR. The current and pulse off time were most significant machining parameter for MRR. It was also mentioned that based on minimum number of trails conducted to arrive at the optimum cutting parameters. Taguchi method seems to be an efficient procedure to find the optimum cutting parameters.

Darji Swaraj *et al.* [22] performed experiments and study was conducted for varying machining parameter like polarity, peak current, rotational speed of electrode and pulse on time using taguchi methodology to investigate the machining characteristics of Hastelloy C276 with 0.5 mm graphite rod as electrode. Significant machining parameters for MRR were identified by using signal to noise ratio and ANOVA that the maximum material removal rate (MRR) was obtained at negative polarity, material removal rate was less at 50 rpm and it upsurges up to higher value of rotational speed of electrode due to higher centrifugal force and wreckage was detached effortlessly. Likewise, MRR was low at low peak current of 0.3 A and it increases up to higher value peak current of 2 A.

Yadav *et al.* [23] investigated that the high temperature gradients were generated at the gap during electrical discharge machining (EDM) result in large localized thermal stresses in a small heat affected zone. These thermal stresses could lead to micro-cracks, decreased in strength and fatigue life and possibly catastrophic failure. A finite element model was developed to estimate the temperature field and thermal stresses due to

Gaussian distributed heat flux of a spark during EDM. The effects of various process variables (current and duty cycle) on temperature distribution and thermal stress distribution were analyzed. The results of the analysis showed high temperature gradient zones and the regions of large stresses exceed the material yield strength.

Lauwers *et al.* [24] focussed that ceramic materials have become important for various industrial applications. Many types of these materials have been developed. However, research and development of ceramic materials, especially suited for electrical discharge machining (EDM), is still limited. This paper presented a detailed investigation of the material removal mechanisms of some commercially available electrical conductive ceramic materials through analysis of the debris and the surface/sub-surface quality. ZrO_2-based, Si_3N_4-based and Al_2O_3-based ceramic materials, with additions of electrical conductive phases like TiN and TiCN, had been studied. This paper pointed out that besides the typical EDM material removal mechanisms, such as melting/evaporation and spalling, other mechanisms can occur such as oxidation and dissolution of the base material.

Keskin *et al.* [25] observed that the most important performance measure in EDM was the surface roughness; among other performance parameters like material removal rate (MRR) and tool wear rate (TWR). In this study, experiments were performed to determine parameters effecting surface roughness. The data obtained for performance measures hade been analyzed using the design of experiments methods. A considerably profound equation was obtained for the surface roughness using power, pulse time, and spark time parameters.

Patel *et al.* [26] performed an experimental work on Mild steel with copper, brass and graphite as tool electrodes with kerosene oil as dielectric fluid. MRR was increased with increasing the discharge current for all three electrodes. MRR did not observe linearly with pulse energy, might be due to the possible losses of thermal energy by conduction to surrounding material and dielectric fluid. Copper showed good response in metal removal rate toward high values of discharge current, due to increase in thermal conductivity and electrical conductivity of copper. Brass showed good response in surface finish with all values of current compared to other electrodes. SEM (scanning electron microscope) of EDM surface indicated that molten mass had been removed from surface as ligaments and sheets and also as chunks which got stuck to surface due to molten state. All specimens, machined by different electrodes showed different pattern of HAZs.

Singh and Kumar [27] investigated that EDM was an important manufacturing process for the tool, mould, and dies industries for several decades. The process finds an increasing industrial use owing to its ability to produce geometrically complex shapes as well as its ability to machine hard materials that are extremely difficult using conventional processes. Further, in spite of the recent technical advancement, the conventional machining processes are inadequate to produce complex geometries shapes in hard and temperature resistant alloy and die steels. Keeping these requirements in mind, EDM a non- conventional machining methods have been developed. The current study defined operating principles as discharging sparks, vapor, and erosion processes using heat energy to process parts.

Pachaury and Tandon [28] focused on the technological limitations imposed by the metals. The industrial demand of advanced ceramic materials is continuously on the rise. This demand has called upon the researchers in the manufacturing domain to strive hard to evolve processes that can shape these hard and brittle materials, as near net shape of ceramics is very difficult to achieve with conventional sintering processes. This paper unfolds various research trends that employ EDM to machine insulating ceramic materials. The paper presents a classification of the ceramic materials and a comprehensive overview of EDM processes, along with its variants, including the hybrid ones, to machine various ceramic materials like ZrO_2, Al_2O_3, Si_3N_4, SiC and their composites. Significant benchmarks for the machining of insulating ceramics have been identified and presented. The primary objective of this paper is to present a broader range of work that has been done towards machining of advanced ceramics. This overview includes not only the experimental work but also the finite element and numerical simulation models established to study the machining of insulating ceramics via spark discharges. The challenges associated with the machining of insulating materials with EDM process are discussed and these challenges are contrasted with the capabilities of the process to machine their composites.

Pei *et al.* [29] investigated that in electrical discharge machining (EDM) process, tool wear is an inevitable phenomenon that adversely affects the geometrical accuracy of machined features. In this paper, a model of tool wear in EDM was proposed, which accounts for the electric field inside the dielectric fluid using electromagnetic (EM) theory. The spark was proposed to occur at the position where the local electric intensity reaches maximum and exceeds the breakdown strength of the dielectric fluid. This model ws shown to provide the physical insight of the real EDM situation, and to give a more accurate prediction of tool wear compared with traditional geometric property based modeling. With these merits, the proposed model can be applied to predict tool wear in various machining processes. To evaluate this model, simulations of EDM die sinking and ED milling were carried out. The results by this electric field model were compared with both geometric model and experiments. By analyzing the profiles of the tool end, the differences in mechanism between the electric field and geometric model were identified. In addition, this electric field model was also applied to simulate the conic tool forming process in the fix-length compensation with micro-milling, which cannot be thoroughly addressed by the geometric model. The model presented in this paper is capable of capturing the key features of the tool wear in a variety of machining processes.

Pham *et al.* [30] focused on the planning of the EDM process and the electrode wear problem. Special attention was paid to factors and procedures influencing the accuracy achievable, including positioning approaches during EDM and electrode grinding. This paper had given an overview of the main issues affecting the performance and limiting the application of micro-EDM. The presented results could help to plan the process within the expected tolerances. When assigning process tolerances for micro-EDM all aspects of the process, such as type of electrode grinding, type of positioning and duration of the operation, should be considered. All these activities accumulated errors, which was took into account. To remain competitive as a micro-manufacturing technology, micro-EDM processes were used reliable algorithms and strategies with repeatable results. The proposed strategy for micro-milling replaced the complex calculations of other existing methods with simple length measurement. This made the new strategy attractive to industry.

Murray *et al.* [31] documented that during electrical discharge machining (EDM); ablated work piece material was rapidly solidified upon ejection into the dielectric and thought not to become reattached to the electrode surfaces. After the machining of high aspect ratio slots, SEM and EDS techniques along with single discharge and cross sectional analysis were used to explain that debris reattachment onto the tool electrode did not occur randomly but was dependent on its re-melting in the dielectric by the secondary discharge process. The subsequently bonded material was present mainly in the centre of the discharge crater, with no attachment occurring outside of discharge affected regions. The surfaces of electrodes subject to intense secondary sparking were therefore liable to transient surface properties dependent on the composition of the deposited material. It was also observed that the deposited material on the tool electrode could offer a protective effect against wear from further secondary discharges and so potentially enhanced tool life. Also, several other process parameters (polarity, work piece/ tool materials, dielectric type) could be modified to examine their effect on rate and mode of deposition or material transfer.

Trych [32] focused on the carbon fibers behavior under EDM condition especially the tool wear, which was the key feature for a material to be considered a good tool material for electrodes. Experiments and results of different machining parameters that had a major influence on the process would be introduced. The analysis answers the question of electrode wear which was different comparing to standard electrodes and determines the best parameters for machining. The planned tests were also used to verify the newly designed experimental setup. Sometimes a deflection of the fiber after short circuit was noticeable. The values of voltage threshold for detecting short circuits were carefully choosen. The back movement of the electrode which occurred frequently in certain trials consumed time that can be used for the proper machining. This also influenced the calculated value of linear tool wear which have taken into account the total time of experiment. It was impossible to estimate or measure the back movement time. Nevertheless, the setup for experiments with carbon fibers electrodes was able to manage with planned experiments and for certain values of input parameters the relationship of linear tool wear was considered.

D'Urso *et al.* [33] performed tests by varying several process parameters, namely peak current, voltage and frequency. Tubular electrodes made of two different materials (tungsten carbide and brass) were used. A study of the in-progress material removal rate (MRR) and tool wear ratio (TWR) during the drilling process was performed. Some mathematical laws governing the relation between process parameters and performance indexes were defined. TWR and MRR as a function of the hole depth for different electrode materials were obtained. MRR and TWR evolution during the distinct drilling steps showed different behaviors for the two electrode materials. The technological window of the cumulated MRR underlines a second degree polynomial trend for brass and a linear trend for tungsten carbide. Increasing the hole depth TWR increased for all the considered technologies, due to the evacuation of debris that becomes more difficult. The wear behavior was almost linear for tungsten carbide and logarithmic for brass. Within the limits of the tested conditions, a general scheme for the prediction of TWR range using tungsten carbide and brass electrodes were obtained. A remarkable difference in terms of absolute values of DOC and TR could be related to the electrode material properties. In general, high electrical conductivity resulted in faster drilling process but in a lower dimensional and geometrical precision of the holes.

Hosel *et al.* [34] investigated that insulating materials can also be processed via spark erosion when combined with an assisting electrode. In this work a novel lacquer based assisting electrode was introduced that is suitable to start a sustaining erosion process and was applied easily by doctor knife and screen print techniques. Zirconia samples were structured and the process characterised with respect to removal rate, wear rate and wear removal ratio over the erosion depth. Furthermore the influence of two different dielectrics and two electrode materials was analysed, whereby a strong influence of the dielectric and the electrode material was determined. With the gained knowledge precise channel geometries were generated and characterised.

Chen *et al.* [35] foccused to establish a feasible process and optimize the parameter levels for processing electrically nonconductive ceramics through EDM. The purpose of the present investigation was to optimize the electrodischarge machining (EDM) parameters for machining ZrO_2 ceramic. During the EDM process, the surface of the electrically non-conductive ceramic was covered with adhesive conductive copper and aluminium foils to attain the threshold of electrical conductivity for the EDM process. The machining characteristics associated with the EDM process such as material removal rate (MRR), electrode wear rate (EWR), and surface roughness (SR) were explored through the experimental study according to an L18 orthogonal array based on the Taguchi experimental design method. Analysis of variance was conducted to examine the significant machining parameters affecting the machining characteristics. The experimental results showed that peak current and pulse duration significantly affected MRR and SR, and the adhesive conductive material was the significant parameter correlated with EWR. In addition, the optimal combination levels of machining parameters were also determined from the response graph of signal-to-noise ratios for each level of machining parameters.

Chevalier and Gremillard [36] foccused on the clinical use of ceramics for medical applications and presented and proposed a picture for their evolution in the next 20 years. The position of ceramics in a gradual medical approach, from tissue regeneration to conventional implants, is also discussed. They stated that the need for tough, strong and stable bioinert ceramics should be met by either nano-structured, alumina and zirconia based ceramics and composites or by non-oxide ceramics. Further investigation suggested that nano-structured calcium phosphate ceramics and porous bioactive glasses, possibly combined with an organic phase should present the desired properties for bone substitution and tissue engineering.

Kucukturk and Cogun [37] presented a new method for machining of non-conductive ceramic workpieces in electric-discharge machining (EDM). Machining surfaces of nonconductive workpieces were coated with a conductive layer (CL) and graphite powder was added to dielectric fluid for machining. Al_2O_3, ZrO_2, SiC, B_4C and glass workpiece samples were machined by using the method. Different machining conditions were tested for each sample and optimum machining parameters were determined. Effect of electrical conductivity, thermal conductivity and melting point of workpieces on material removal rate (MRR) was investigated. Optical microscope and SEM (Scanning Electron Microscope) surface photographs of workpieces taken after machining have also been presented and discussed.

Liu *et al.* [38] presented a new process of machining insulating ceramics using electrical discharge (ED) milling. They investigated that ED milling uses a thin copper sheet fed to the tool electrode along the surface of workpiece as the assisting electrode, and uses a water-based emulsion as the work fluid. This process was able to effectively machine a large surface area on insulating ceramics. The machining principle of the process has been introduced. The effects of tool polarity, peak voltage, rotational speed of tool electrode and feed speed of workpiece on the process performance have also been investigated.

Ferraris *et al.* [39] investigated the micro-EDM behaviour of an Al_2O_3 and ZrO_2 based electrically conductive ceramic composites. The influence of the generator parameters on material removal rate (MRR), relative tool wear (TWR), surface quality (SQ) and material removal mechanism was investigated towards the definition of suitable micro-EDM technologies. The study was based on a design of experiments, supported by a fundamental investigation of the generator parameters. Similar variations trends to the machining of steel were observed within the investigated process window, for exception of the tool wear performance. The developed EDM technologies were finally validated through the fabrication of industrial demonstrators.

Mehta *et al.* [40] reviewed the development of conductive ceramic materials followed by the progress of EDM technology in this context from its initiation to present state. The discussion is extended to key research areas such as optimizing the material removal, monitoring electrode wear, effect on surface quality. The present and prospering application ranges of such materials have also been accounted for. Majority of work concentrates on improvement in process efficiency, optimization of process variables and process monitoring and control. Noteworthy efforts had been applied to reveal the effect of electrical and non-electrical parameters on response parameters for various electrodeworkpiece material combinations.

Lajis *et al.* [41] reported on the cutting of tungsten carbide ceramic using electro-discharge machining (EDM) with a graphite electrode by using Taguchi methodology. The Taguchi method was used to formulate the experimental layout, to analyse the effect of each parameter on the machining characteristics, and to predict the optimal choice for each EDM parameter such as peak current, voltage, pulse duration and interval time. It was found that these parameters have a significant influence on machining characteristic such as metal removal rate (MRR), electrode wear rate (EWR) and surface roughness (SR). The analysis of the Taguchi method revealed that, in general the peak current significantly affects the EWR and SR, while, the pulse duration mainly affects the MRR. Experimental results have been provided to verify this approach.

Lee and Li [42] reported the influence of opertaing parameters of EDM of tungsten carbide on the machining characteristics. The effectiveness of the EDM process with tungsten carbide was evaluated in terms of the material removal rate, relative wear ratio and the surface finish quality of the workpiece produced. It was observed that the copper tungsten was most suitable for the use as tool electrode in EDM of unsten carbide. Better machining performance was obtained generally with the electrode as the cathode and workpiece as the anode. Tool with negative polarity gave higher material removal rate, lower tool wear and better surface finish. Dielectric flushing pressure was found to be optimum at 50kPa. For precision machining of tungsten carbide the optimum condition of relative wear ratio and surface roughness takes place at a gap voltage of 120V, discharge current of 24A, pulse duration of 12.8μs, pulse interval of 100μs, dielectric flushing pressure of 50kPa and copper tungsten (CuW) as the tool electrode materials with negative polarity. The study confirmed that there exists an optimum condition for precise machining of tungsten carbide although the condition may vary with the composition of the material, the accuracy of the machine and other external factors.

1.9. Objectives of the Present Research Work

From the review of past research works it is seen that a lot of theoretical and experimental works have been carried out for proper understanding of the basic process of EDM and also for identification of actual process parameter setting to optimize EDM performance criteria. Some researchers also applied the EDM technique for machining of difficult-to-cut materials, which cannot be machined by any other conventional techniques. Non-conductive ceramic materials are one of those materials which are really difficult to machine using any conventional machining method thus in the last few years researchers have shifted their focus to successful machining of these materials using non-traditional machining methods e.g. EDM, USM etc. Various advancements have also taken place in the research trends of machining ceramics with the help of EDM. Regardless of all the research and advancements that have taken place the main aim of the researchers have always been improving material removal rate (MRR), tool wear rate (TWR), overcut, taperness, circularity, surface roughness etc.

Hence, the objectives of the present research work concentrates on the followings:

(i) To select the suitable ceramic material to perform drilling in EDM.

(ii) To select the appropriate method for machining the above selected ceramic material.

(iii) To search out the most influencing process parameters and their suitable range.

(iv) To modify the existing setup for performing the EDM drilling on ceramic material.

(v) To study the impact of most influencing process parameters on the major responses.

(vi) To select best set of parametric combination of process parameters utilizing different optimization techniques for improvement of the accuracy of the ED-drilled hole.

2. MATERIAL REMOVAL MECHANISM DURING MACHINING OF CERAMICS USING ELECTRO-DISCHARGE MACHINING PROCESS

Electrical discharge machining requires a minimum electric conductivity about $10^{-2}\Omega^{-1}cm^{-1}$. This demand is fulfilled by metallic materials. The minimum electric conductivity constitutes a critical factor for the possibility of electrical discharge machining of ceramics. As an overview, below Fig.2.1 shows the electrical conductivity for selected metallic materials and ceramics [43]. Electrically conductive ceramics like silicon doped silicon carbide (SiSiC), titaniumdiboride (TiB_2), or titanium nitride (TiN) can be machined by EDM like metallic materials. For nonconductive ceramics like Zirconia (ZrO_2), aluminium oxide (Al_2O_3), or silicon nitride (Si_3N_4), the electric conductivity is too low to achieve an electrical discharge between tool and workpiece and therefore using a conventional EDM process is not possible. Therefore we have to look for some other possibility which will allow machining of nonconductive ceramics.

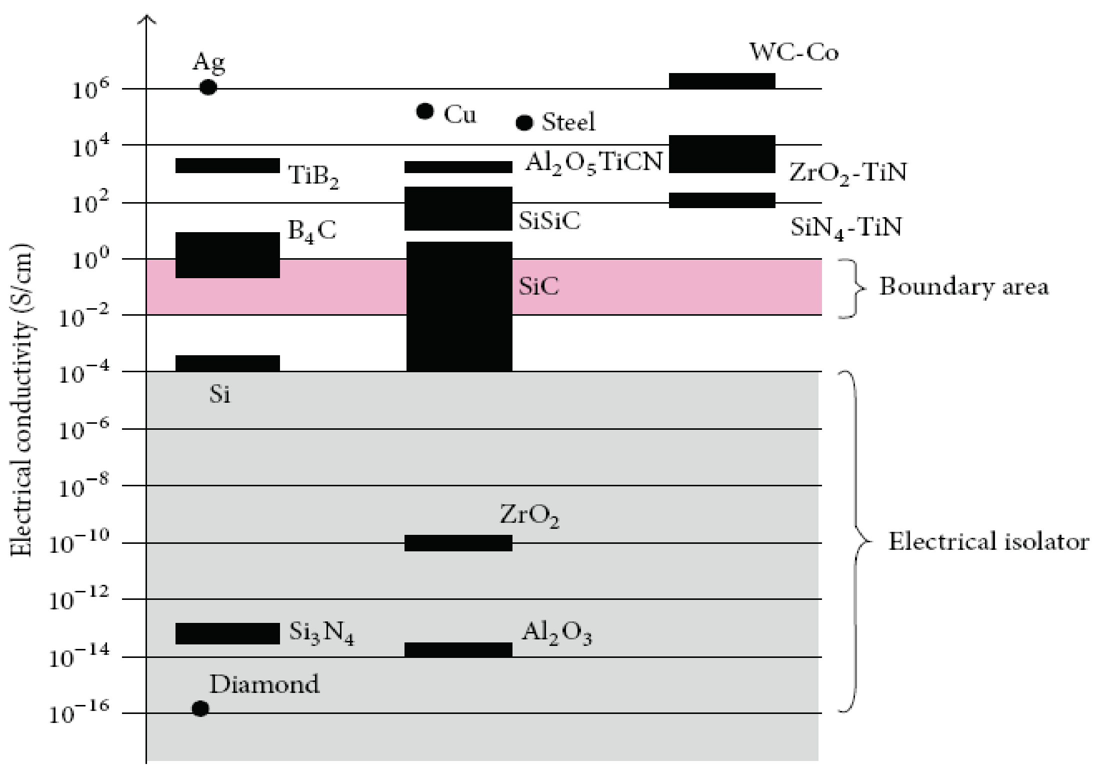

Fig.2.1. Overview of materials and their electrical conductivity

2.1. Material Removal Mechanism During Electrodischarge Machining of Ceramic Materials

Electrical discharge machining is a process which is based on electrical discharges between two electrodes, the tool and the workpiece. The ablation of the material is realised by melting and evaporation of material.. Tool and workpiece are separated by a dielectric medium, either dielectric oil or deionised water. For realising an electrical discharge, a voltage is applied between tool and workpiece and the distance between the electrodes is decreased. By reaching the breakdown voltage of the dielectric medium, a discharge takes place, establishing a plasma channel which causes a current flow. Thus, temperatures of more than 10000K occur and the material gets melted and evaporated, creating an expanding gas bubble. Stopping the input of the energy leads to a collapse of the plasma channel and therefore to an end of the discharge. The formed gas bubble collapses, too. The particles of the removed material are flushed away by this and the flow of the dielectric medium. By applying a voltage between tool and workpiece again, the process repeats in the same procedure. This is the material removal process of electrical discharge machining.

(i) Doped ceramics method

It is possible to influence the conductivity of insulating ceramics like ZrO_2, Al_2O_3 and Si_3N_4 by doping. To achieve this, a secondary electrically conductive phase is incorporated into the material which enables the possibility to machine these ceramics by EDM. Successful approaches were achieved with the reinforcements of TiB_2, WC, ZrB_2, TiC, TiCN, and TiN in zirconia and yttrium nitrate (YN) has been used for realising an electrically conductive SiC ceramic [44]. Generally metals have free lattice electrons as charge carrier but ultrapure ceramics possess no charge carrier that's why metals are known to be natural conductors. As mobility of ions of ceramics is restricted by their integration in structure even at high field strength, no current is conducted through ceramics. Current can be made to pass through this non conductor by doping it with some natural conductor during manufacturing. In polar bonded material, conductivity can be introduced by freeing additional electrons which have certain mobility. For ZrO_2 and

Al_2O_3, the incorporating with TiN and TiCN has been reported as successful attempt to realise machining by EDM.

One disadvantage of this procedure is the influence of these reinforcements on the mechanical properties of the material, which could lead to undesirable effects. By increasing of the content of doping, a decrease in the hardness, the fracture toughness and the flexural strength of ceramics can be observed.

(ii) Assisting electrode method

In this procedure, a conductive layer is applied on the surface of the insulating ceramic. Thereby, the process can initially be started by machining this conductive starting layer. The procedure is based on the effect that machining of the thin starting layer material also causes an ablation of the work piece material below. Additionally, the hydrocarbons in dielectric oil are disintegrated and carbon is available. On the ceramic surface, a secondary thin conductive layer is formed which enables a continuous EDM process for these insulating ceramics. By thoroughly controlling this process,it is possible to achieve a stable repetition of this sequence of removing the conductive layer and the underlying workpiece material and the deposition of a secondary layer on to the surface. The machining is possible as long as the conductive layer can be generated reliably. The formation of a conductive layer during the assisting electrode method also leads to a different shape of the discharge pulses. The scheme of the assisting electrode method is shown in Fig.2.2 below

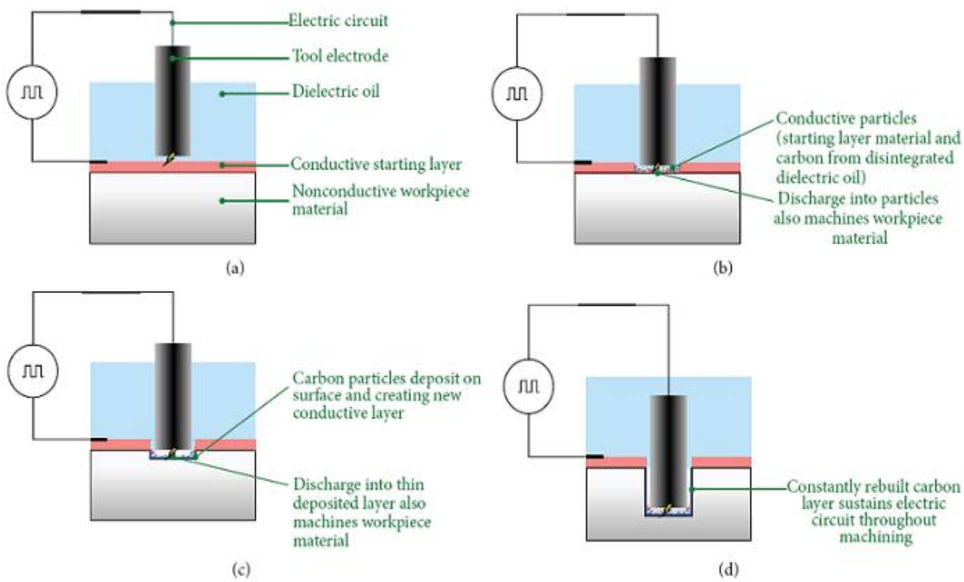

Fig.2.2. Assisting electrode scheme for machining of non-conductive ceramics [45]

At the interface of the assisting electrode and the non-conductive ceramics, instabilities in the machining processes are prone to occur due to the formation of intermediate conductive layer and this facilitates in the material removal through electric discharges

The molten crater in EDM can be assumed to be hemispherical in nature with a radius r which forms due to a single pulse or spark. Hence material removal in a single spark can be expressed as

$$\Gamma_s = 2/3\ \pi\ r^3 \qquad \text{(Eq.1)}$$

Now, the energy content of a single spark (Es) is given as

$$Es = VIt_{on} \qquad \text{(Eq.2)}$$

Where, V is open circuit voltage, (V) , I is the current, (A) and t_{on} is on time, (µs).

A part of this spark energy gets lost in heating the dielectric, and rest is distributed between the impinging electrons and ions. Thus the energy available as heat at the workpiece (E_w) is given by

$$E_w \propto E_s$$

$$E_w = K\ E_s \qquad \text{(Eq.3)}$$

Now it can be logically assumed that material removal in a single spark would be proportional to the spark energy. Thus

$$\Gamma_s\ \alpha\ E_s\ \alpha\ E_w$$

$$\therefore\ \ \Gamma_s = g\ E_s \qquad \text{(Eq.4)}$$

Now material removal rate is the ratio of material removed in a single spark to cycle time. Thus

$$\text{MRR} = \frac{\Gamma s}{tc} = \frac{\Gamma s}{ton + toff}$$

$$\text{MRR} = g\frac{VIton}{ton+toff} = g\ \frac{VI}{1+\frac{ton}{toff}} \qquad \text{(Eq.5)}$$

The above is the mathematical model for MRR in RC circuit in EDM. However, for machining of ceramics by EDM the principle is same but mechanism is a little different than the conductive materials. In ceramics the melting and evaporation process is followed by thermal ablation process. There are two different possibilities which allow machining of nonconductive ceramics. The first option is a doping of the ceramics by a conductive phase. Thus, it is possible to increase the conductivity above $10^{-2}\Omega^{-1}cm^{-1}$ which enables machining of these ceramics by EDM. The second option is the so-called "*Assisting electrode method*." For this procedure, an electrical conductive starting layer is used to begin the process.

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2.2. Tool Electrode For EDMing of Ceramic Materials

The selection of tool material is an important factor, because the performance of EDM depends on the combination of workpiece and tool materials. Up-to-date known and able tool electrode materials for EDM are copper, brass, tungsten and tungsten composites such as tungsten copper or tungsten carbide. The attractive attributes of copper are its high electrical and thermal conductivity. Copper has the highest conductivity of any non-precious metal and one that's 65% higher than aluminium. This, combined with its high ductility, medium strength, ease of joining and good resistance to corrosion, makes copper the first choice as a tool electrode. Copper also has corrosion resistance properties and has good machinability. Moreover it is easy to obtain, very consistent in quality and low in cost as compared to other electrodes.

Brass is also a well known material used as a tool electrode in EDM because of its high electric and thermal conductivity, easily available, consistent in quality and low cost. But due to low melting point, this tool material wears rapidly in the high machining temperature. Also, the fabrication and low metal removal rate make this tool materials low acceptance in EDM.

Tungsten is a metal of very high strength, density and hardness. With a melting point near 3400ºC, it resists thermal damaging effects of the EDM process very well. Disadvantages of tungsten are a very high material price. It is also difficult to machine because of its high hardness. To make tungsten more attractive for certain applications it is combined with ductile materials such as copper. The resulting material, tungsten copper, is easier to machine, more conductive than normal copper and extremely wear resistant. Especially in the field of micro-structuring and surface finishing, copper tungsten is used as the tool electrode material.

Tungsten carbide (WC) is a chemical compound containing equal mount of tungsten and carbon atoms. It is approximately twics as stiff as steel, with young's modulus of approximately 540-700 GPa. Tungsten carbide has very high strength for a material so hard and rigid. Compressive strength is higher than virtually all melted and cast or forged metals and alloys. Moreover thermal as well as electrical conductivity of tungten carbide is also desirable to be used as tool electrode.

2.3. Dielectric Fluids for EDMing of Ceramic Materials

The dielectric fluid has several functions in the EDM process. It isolates the tool electrode from the workpiece electrode to achieve a high current density in the plasma channel. It also cools down the heated surfaces of the electrodes and exerts a counter pressure to the expanding plasma channel. Flushing with dielectric fluid removes the particles after the discharge process and prevents developing particle linkages causing process interruptions by short circuit or damage of the electrodes' surfaces. The dielectric fluid also acts as a coolant for the seconday purpose. There are two main types of dielectric fluids one is deionized water and other is dielectric fluids based on hydrocarbon compounds, also known as dielectric oil or EDM oil. The differences are depicted in the Table 2.1.

Table 2.1. Difference between Hydrocarbon Dielectric Fluid and Deionized Water

Type of dielectric fluid	**Hydrocarbon dielectric fluids**	**Deionized water**
Electrical conductivity	<0.1 W/m-K	1 W/m-K
Technological behaviours	High material removal rate, small tool wear, big influence on peripheral zone	High material removal rate, High surface quality, high wear
Properties	No corrosion of work piece, no deionization necessary, special disposal, low flash point	Not flammable, no hazardous vapors, no special disposal, corrosion
Environmental impact	Hazardous vapors	Non hazardous vapors
Applications	Die sinking	Die sinking & wire electrical discharge machining.

2.4. Process Parameters of EDMing of Ceramic Materials

In theory, we can say that the process parameters of EDM are those parameters which directly have effect on the output responses. Electro discharge machining uses electric discharge where electrodes discharges pulses and cut away the metal with help of dielectric fluid for better machining accuracy. It is also stated that the principle of both macro EDM as well as micro EDM is similar, where the process mechanism is based on an electro-thermal process that relies on a discharge through a dielectric in order to supply heat to the surface of the work piece, various EDM process parameters are discussed below.

(i) Discharge voltage

Discharge voltage in the EDM is related to the spark gap and breakdown strength of the dielectric is expressed in volt (V). Before current can flow, the open gap voltage increases until it creates an ionization path through the dielectric. Once the current starts to flow, voltage drops and stabilizes at the working gap level. The preset voltage determines the width of the spark gap between the leading edge of the electrode and work piece. Higher voltage settings increase the gap, which improves the flushing conditions and helps to stabilize the cut. With increasing discharge voltage electric field strength increases which leads to increment of MRR, TWR and surface roughness.

(ii) Peak current

This is related to the amount of power used in discharge machining, measured in units of amperage (A) and is one of the most important machining parameter in EDM. During each pulse on-time, the current increases until it reaches a preset level, which is known as the peak current. Higher currents will improve MRR but at the cost of TWR and Surface finish.

(iii) Pulse-On-Time (T_{on})

Each cycle has an on-time and off-time that is expressed in units of microseconds. Since all the work is done during on-time, the duration of these pulses and the number of cycles per second are important. Metal removal is directly proportional to the amount of energy applied during the on-time. The energy is controlled by the peak current and the length of the pulse on-time. The resulting crater is deeper and broader, than a crater produced by a shorter on-time. Excessive on-times can be counter productive when the optimum on-time for each electrode-work material combination is exceeded, material removal rate starts to decrease. The cycle is completed when sufficient off-time is allowed before the start of the next cycle.

(iv) Pulse-Off-Time (T_{off})

It affects the speed and stability of the machining. Shorter the off-time, the faster is the machining operation. However, if the off-time is too short, the produced machined bi-products cannot be removed and by the flow of the dielectric and the fluid will not be deionized which will cause the next spark to be unstable. Unstable conditions cause erratic cycling and retraction of the advancing servo. This slows down cutting more than long, stable off-times. Off-time must be greater than the deionization time to prevent continued sparking at one point.

(v) Polarity

The polarity of the electrode can be either positive or negative. The current passing the gap creates high temperatures causing material evaporation at both electrode spots. As the electron processes show quicker reaction, the anode material is worn out predominantly. This causes minimum wear to the tool electrodes and becomes of importance under finishing operations with shorter on-times. When tool is positive and workpiece negative polarity then it is called reverse polarity and vice versa condition is called straight polarity. In die sinking EDM we use reverse polarity because of high material removal rate as compared to straight polarity, but advantage of straight polarity is that it prevents wear of tool electrode, despite low material removal rate.

(vi) Electrode Gap

The tool servo-mechanism is of considerable importance in the efficient working of EDM and its function is to control responsively the working gap of the set value. Mostly electro-mechanical systems are used. The most important requirements for good performance are gap stability and the reaction speed of the system, the presence of the backlash is practically undesirable electrode Gap.

(vii) Duty cycle (τ)

This is the ratio of on-time relative to total cycle time. This parameter is calculated by dividing pulse-on time by total cycle time. The calculation of duty cycle is given in Eq.6.

$$\tau = \frac{Ton}{Ton+Toff} \qquad \text{(Eq.6)}$$

2.5. Performance Criteria of EDMing of Ceramic Materials

In EDM, performance criteria can be affected by the various factors such as pulse energy i.e. a function of capacitance, voltage, current, dielectric flushing, aspect ratio, debris distribution, dielectric, gap voltage etc. When EDM is employed to generate feature, part or mold, it is necessary to consider these factors for optimal performance criteria. The major EDM performance characteristics are material removal rate (MRR), tool wear rate (TWR), discharge gap, surface roughness and recast layer. Wear ratio (WR), over cut (OC), taperness, roundness etc., are also performance characteristics of the EDM process. Major performance criteria of EDM process are described as follows:

(i) Material removal rate (MRR)

Material removal rate is the amount of removed material from the workpiece material divided by time taken for machining. Generally, MRR mainly depends on the discharge pulse energy (a function of capacitance and voltage). The larger pulse energy results in higher MRR. The increase in voltage and capacitance also increase MRR. MRR also depends on the movement of the tool. MRR can also be increased by increasing the tool moving speed and rotation of the tool in EDM. When drilling a deep hole, the ejection of debris from the machining area becomes difficult. The debris concentration causes the abnormal discharge. One solution to this problem is the application of planetary movement to the electrode or application of vibration to the workpiece. It reduces the occurrence of abnormal discharge and thus improves the MRR. The type of dielectric also influences the MRR. The carbon decomposed from the hydro-carbon oil contaminates the dielectric, resulting in an increase of abnormal discharge occurrence. The de-ionized water does not present such a problem. Therefore, the machining time of the deep hole drilling using de-ionized water is much shorter than the hydro-carbon oil.

(ii) Tool wear rate (TWR)

Tool wear rate is the amount of eroded material from the tool material divided by time taken for machining. TWR increases with an increase of pulse energy (voltage and capacitance). Drilling a deep hole or a blind hole, the ejection of debris from the machining area becomes difficult and the debris concentration causes the abnormal discharge. Planetary movement to the electrode provides an extra space for an effective removal of debris and gaseous bubbles. It was found that in EDM, the electrode area affects the tool wear ratio and it can be improved by the increase of electrode working area.

(iii) Discharge gap

The discharge gap is calculated by dividing the difference between the width of slot and the diameter of the electrode by two. It is increases with an increase of pulse energy, i.e. voltage and capacitance.

(iv) Surface roughness

Electrical discharge machined surface is made up of three distinctive layers consisting of white/recast layer, heat affected zone (HAZ) and unaffected parent material. The EDMed surface tolerates the solidification behavior of the molten metal after the discharge cessation and subsequent phase transformation. The presence of cracks and high tensile residual stresses on the EDMed surface caused by the high temperature gradient has been found. In addition, the EDMed surface has a relatively high micro hardness, which can be explained due to the migration of carbon from the oil dielectrics to the workpiece surface forming iron carbides in the white layer or HAZ. Only through SEM micrographs, one can measure the thickness of these layers. The surface roughness also increases with an increase of pulse energy.

(v) Recast layer

As EDM is a thermal process, it generates a heat affected zone consisting of a recast layer and cracks. The thickness of the recast layer formed on the workpiece surface and the level of thermal damage suffered by the electrode can be determined by analyzing the growth of the plasma channel during sparking. Since the white layer is topmost layer exposed to the environment, it exerts a great influence on the surface properties of the workpiece. The recast layer can be reduced by changing the tool path or layer depth, or can be removed using ECM or laser processes. It is very difficult to measure this recast layer thickness because there is no such instrument which can directly measure this recast layer.

(vi) Heat affected zone (HAZ)

Beneath the recast layer, a HAZ is formed due to rapid heating and quenching cycles during EDM. This layer is approximately 25 µm thick. The heating-cooling cycle and diffused material during machining are the responsible reasons for the presence of this zone. Thermal residual stresses, grain boundary weaknesses and grain boundary cracks are some of the characteristics of this zone. Below HAZ there is a conversion zone characterised by a change in the grain structure from the original structure.

From the above discussions it is clear that EDM performance is influenced by several factors such as, process parameters, properties of workpiece, tool materials and dielectrics etc. By changing any of the above parameters or characteristics changes the response of the electro discharge machining process. The input and output relation is shown in the Fig.2.3

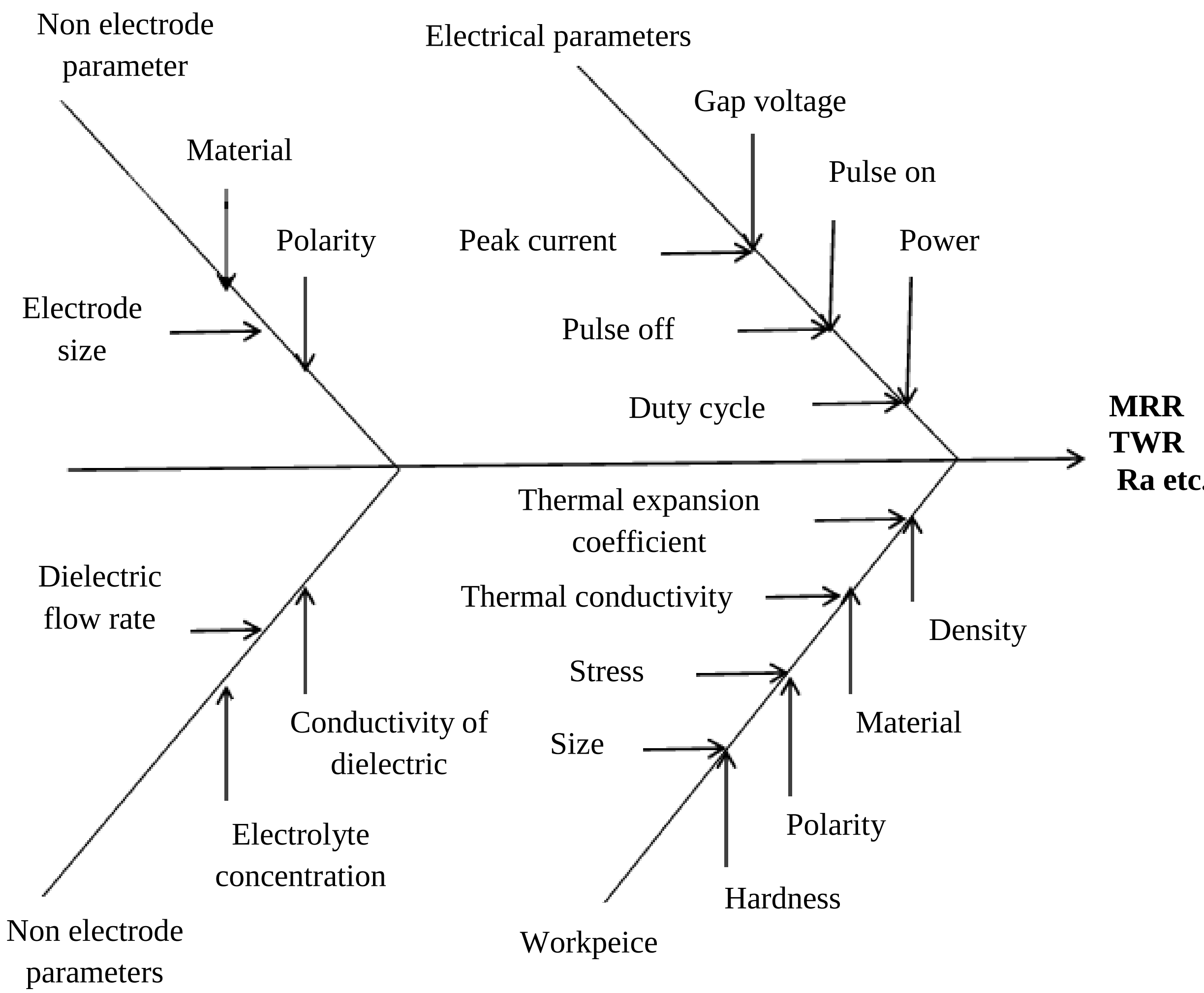


Fig.2.3. Input and output relationship diagram of EDM process

3. EDM SETUP FOR EXPERIMENTATION

Experiments have been carried out using S-35 ZNC Die-Sinking EDM set-up equipped with SRP Control Panel made by Elektronica Machine Tools Private Limited, Pune. The main specifications of the experimental EDM set-up are shown in Table 3.1 below.

Table 3.1. The main specifications of the experimental EDM set-up

Work Tank Dimensions	600 mm × 370 mm × 250 mm	Maximum Job Weight	150 Kgs
Table Size	350 mm×200 mm	Dielectric Tank Capacity	100 Lits
X – Axis Travel	200 mm	Machine Weight	450 Kgs
Y – Axis Travel	120 mm	Gross Weight	600 Kgs
Z – Axis Tarvel	150 mm	Day Light	410 mm
Maximum Job Height	140 mm	Throat	250 mm
Maximum Electrode Weight	50 Kgs	Overall Dimensions	800 mm × 800 mm × 1800 mm

The experimental set-up consists of three sub-systems like main machining chamber, power supply and control unit and dielectric supply unit. The photographic view of EDM set-up is shown in Fig.3.1

Fig.3.1. Photographic view of S-35 ZNC Die-Sinking EDM Machine

3.1. Hardware Unit

S-35 ZNC Die-Sinking EDM has various sub-systems, e.g. main machining chamber, tool holding unit, job holding unit etc. which are described as below:

3.1.1. Main machining chamber

In the S-35 ZNC Die-Sinking EDM, the dimension of the main machining chamber is 600mm × 370 mm × 250 mm. The body is made up of cast iron. A workpiece holding vice is generally kept in the main machining chamber, which is used to hold the job and that is also made up of cast iron. Four clamping devices made up of brass, are generally used to hold the job rigidly. A pressure gauge is used to control the flushing pressure of dielectric. Generally two types of valve are used for two different purposes in the left side of main machining chamber. One is the inlet ball valve and another is injection flushing valve. Inlet ball valve is used to control the amount of dielectric enters into the main machining chamber and injection flushing valve is used to maintain a certain level of dielectric at main machining chamber. There is also a drain handle at the left side of main machining chamber for drain out the dielectric after the machining operation. Two circular handle is used manually for precision movement of the work-table. At the inner right side of the chamber a floating valve is used to maintain the dielectric level at 50 mm above the workpiece to avoid the fire related accident. A schematic and photographic diagram of main machining chamber is shown in the Fig.3.2 and Fig 3.3 respectively

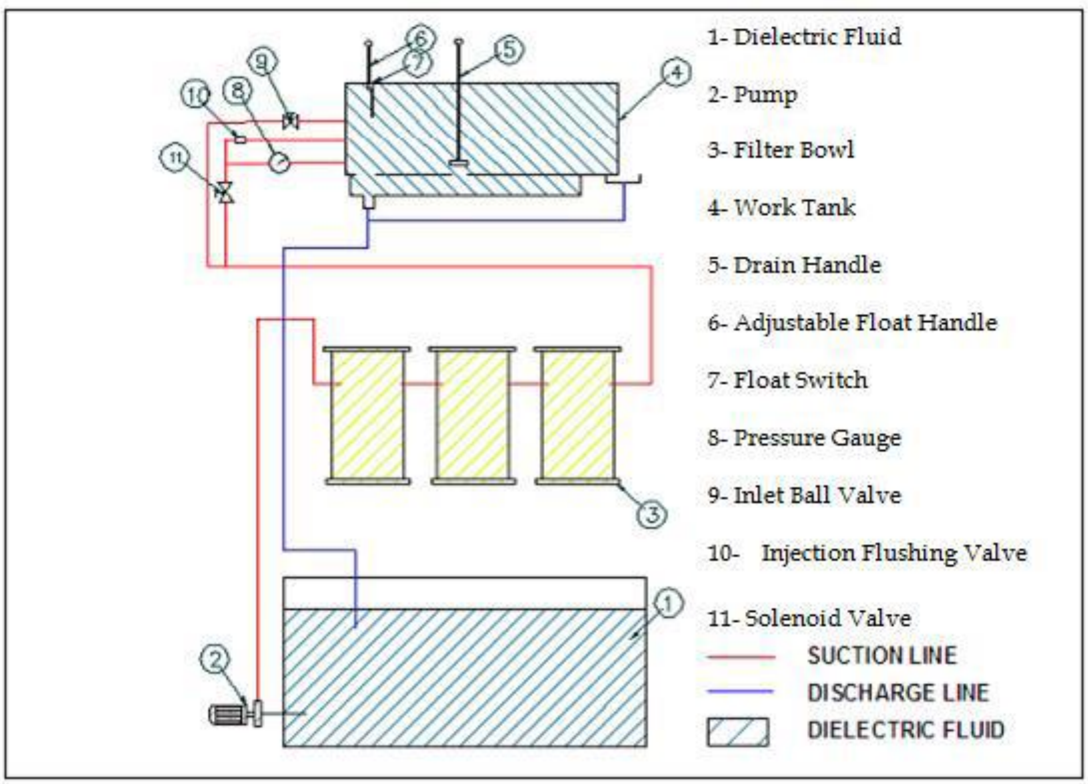


Fig.3.2. Schematic diagram of main machining chamber and dielectric supply unit [46]

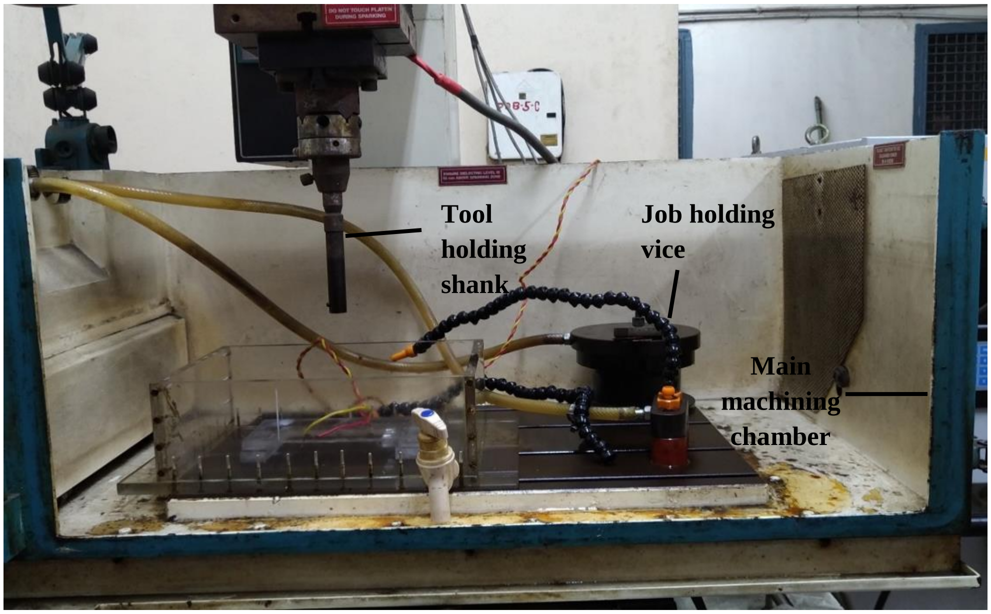


Fig.3.3. Photographic view of main machining chamber

3.1.2. Tool holding unit

In the existing EDM set up it cannot be possible to hold a tool in the shank of the EDM tool holding machine since the diameter of the tool is just 1 mm. So, there has to be an alternative provision of tool holding device in order to hold the tool in proper place. For this purpose a three jaw chuck tool holding device has been used for the experimentation. The tool holding device has teeth cut out on it so as to tighten and loosen the tool in it with the help of a key, by engaging and disengaging the key in the teeth of the tool holding device. The engagement and disengagement is done by keeping the teeth of the key and tool holding device at 90º with respect to each other. This tool holding device is then fitted into the shank of the EDM machine with the help of allen key, so as to perform the experimentation. The orthographic and photographic views have been shown in the Fig.3.4 and Fig.3.5 respectively.

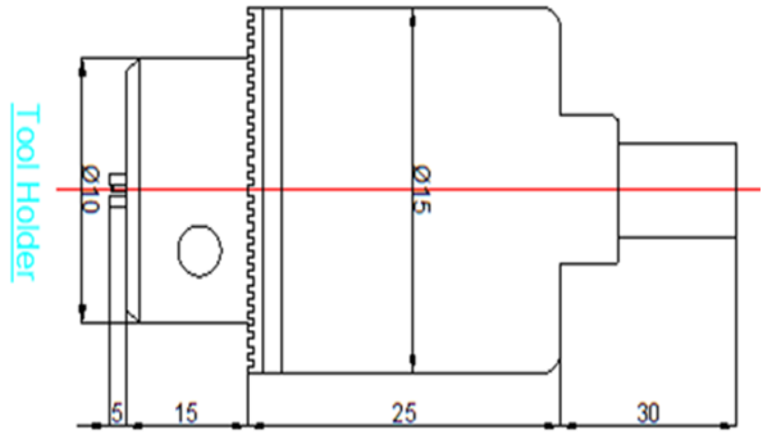


Fig.3.4. Orthographic view of the tool holder

Fig.3.5. Photographic view of tool holder

3.1.3. Job holding unit

In the existing EDM set up there is a workpiece holding vice kept in the main machining chamber on which the jobs are held. Alumina workpiece of 5 mm thickness is clamped by both the sides on this vice and machining is performed. First Alumina (Al_2O_3) workpiece thickness being 5 mm, hence could be held on the vice in the main machining chamber but the thickness of the other Alumina(Al_2O_3) workpiece being 1 mm, cannot be clamped on this vice therefore a separate job holding unit is prepared in the modified machining chamber. The total job holding unit is fixed at the bottom of the modified machining chamber and slots have been cut in order to hold the Alumina (Al_2O_3) on it with the help of nut, bolt and washers. The photographic view of the job holding units of both the main machining chamber and modified machining chamber has been shown in Fig.3.6. and Fig.3.7 respectively.

Fig.3.6. Job holding vice in main machining chamber

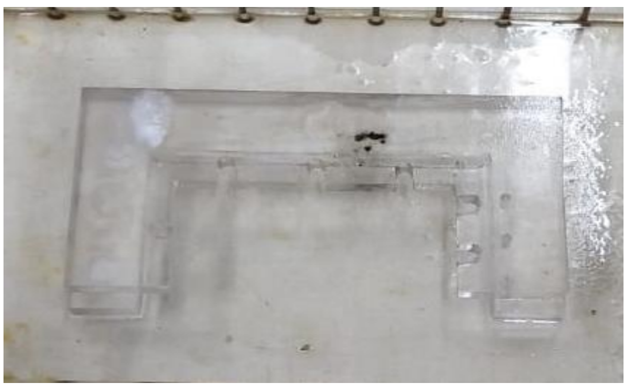


Fig.3.7. Job holding unit in the modified machining chamber

3.2. Power Supply Unit

S-35 ZNC Die-Sinking EDM has 415V, 3 Phases, 50 HZ supply unit. This power supply unit is of static pulse generator type. Using the latest embedded system it can be able to produce the feature that expanded automatic control and monitoring during the EDM process, resulting in much higher efficiency. The design features an automatic monitoring system against current surges. MOSFETs are protected against overload when properly grounded the power supply unit will not produce shocks of other electrical hazards. A stabilizer is used to supply continuous DC power supply to the control panel. A brief technical specifications of the power supply unit has been listed in the Table 3.2

Table 3.2. Technical specifications of the power supply unit

Model Name	S-35 ZNC Die-Sinking EDM
Supply Voltage	415V± 5%, 3 Phases, 50 HZ
Open Gap Output Voltage (V)	65 ± 5%
Power Factor	0.8 (Approx.)
Connected Load (KVA)	3 KVA
Machining Current Max (Amps)	35 Amp
Current Range Selection	Programmable
Pulse On Duration	2-2000 μs
Weight	80 g (Approx.)

S-35 ZNC Die-Sinking EDM is also equipped with D300 Control Panel made by Elektronica Machine Tools Private Limited, Pune. In the control panel there is a data display TFT LCD monitor. It has basically two modes, one is ‘DRO’ mode and another is

‘EDM’ mode. In the ‘DRO’ mode we can set the workpiece position. In the ‘EDM‘ mode we can set all the input parameters like peak current, gap voltage, pulse-on-time, duty ratio, sensitivity, arc sensitivity and the Z-depth etc. The interelectrode gap is set also by using this control unit. It is fully automatic control provided with a joystick and can be manually controlled as well, by clicking the sticky keys on the control panel.

3.3. Dielectric Supply Unit

The dimension of the main machining chamber is 800 mm × 800 mm ×1800 mm. The capacity of the tank is approximately 100 liters. The machine basically recommend ESSO- MENTOR - 28/ BAYOL 35 as dielectric fluids though, equivalents may also be used. Dielectric is supplied through the nozzles to the inter-electrode gap for the removal of debris. Dielectric is circulated by the pump through the filters such as a fresh dielectric always remains in the main machining chamber. Three filters bowls with 10 µm of mesh size is used to filter the dielectric every time of its recirculation. A pressure gauge is used to control the flushing pressure.

3.4. Servo Controlled Unit

The servosystem is commanded by signals from the gap voltage sensor system in the power supply and controls the infeed of the electrode or workpeice to precisely match the rate of material removal. If the gap voltage sensor system determines that a piece of electrically conductive material has bridged tha gap between the electrode and workpeice, the swrvosystem will react by reversing direction until the dielectric fluid flushes the gap clear, the infeed resumes and the cutting continues. The selection of dielectric flushing technique has direct effect on the function of the servosystem. If the flushing system is inefficient in removing the process by-products from the cutting gap, the servosystem may have to spend most of the time reversing to clear the cutting gap. This results in extremely long cycles. However if the flushing technique is effectively removing the by-products, the servosystem will spend almost no time retracting, resulting in much faster cycles. Other auxillary fucntions related to the servosystem and most often used when drilling include touchoff sensing, breakthrough sensing and electrode refeed.

3.5. Modification of Machining Chamber

The machining chamber of experimental EDM set-up, made by ELECTRONICA is modified in order to fulfill the objectives of the present work. The new machining chamber is made with perspex material. The machining chamber is actually a box type rectangular container having dimension of 350 × 300 × 100 mm. The modified job holding device is attached with the table which is also consisting of three pieces of perspex plates in the form of a C-shape. Total job holding table is fixed at the bottom of machining chamber. Main purpose of the machining chamber is to hold the Alumina(Al_2O_3) workpiece of 1mm thickness. Photographic and orthographic views have been depicted in the Fig.3.8 and Fig.3.9 respectively.

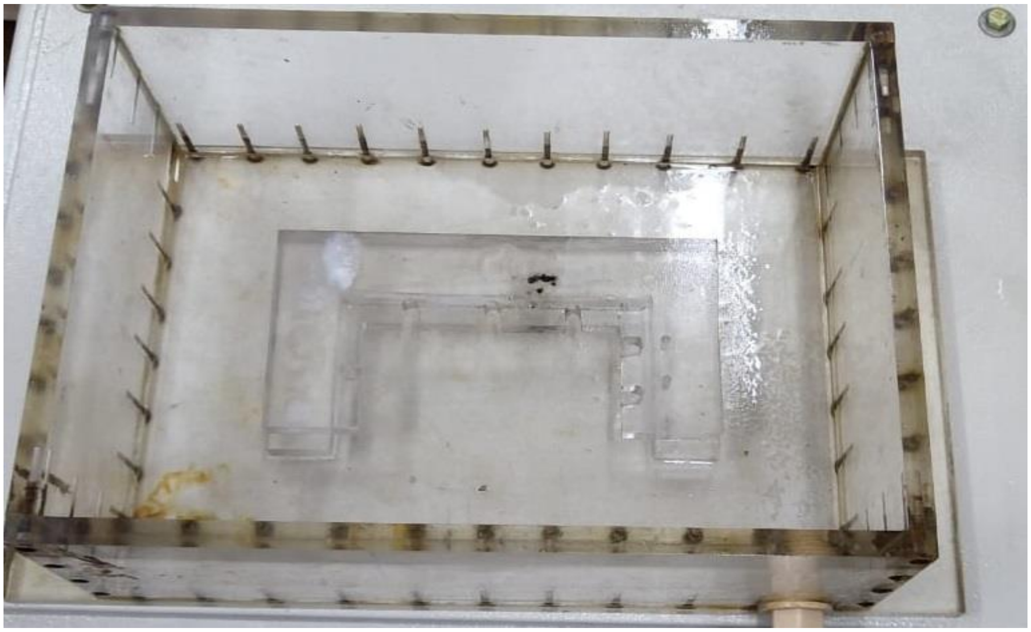


Fig.3.8. Photographic view of the modified machining chamber

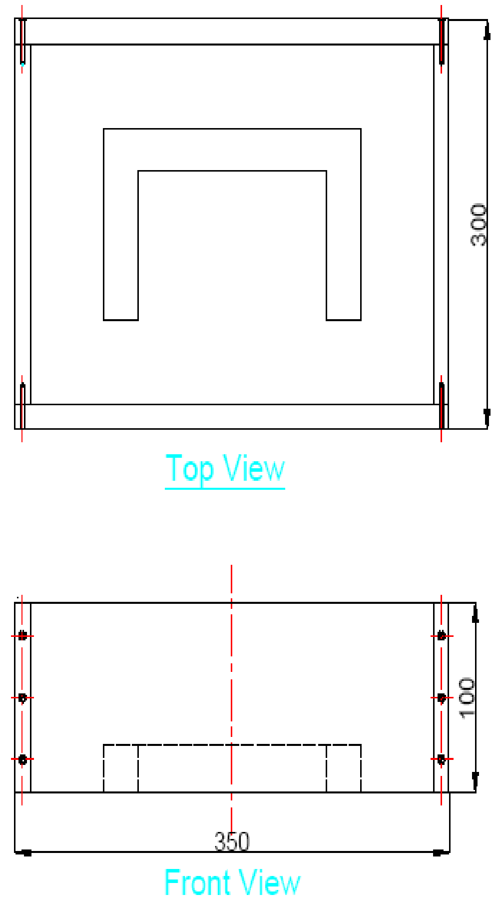


Fig.3.9. Orthographic view of the modified machining chamber

4. PLANNING FOR THE PRESENT RESEARCH WORK

Although, conventional EDM process have significantly improved the performance criteria such as material removal rate (MRR), tool wear rate (TWR) etc., but still low efficiency and poor surface quality for low or non-conductive and difficult to cut materials such as ceramics are the key problems restricting its development. Therefore it is the most challenging issue to improve the machining efficiency and surface quality of ceramic materials by performing EDM. For this purpose some techniques such as doping ceramic materials and assisting electrode method have been incorporated in EDM to increase the machining rate, accuracy and surface finish of ceramics.

4.1. Experimental Plan

Experimental investigations and the studies of many research works have been revealed that the most influencing process parameters in EDM are peak current, polarity, pulse on-time and flushing pressure of dielectric fluid. In the present research work attempt has been made to investigate the effects of different process parameters on EDM performance characteristics such as material removal rate (MRR), tool wear rate (TWR) and overcut (OC) on the ceramic materials by using assisted electrode method. During the machining, peak current (I_p), on time (T_{on}) and flushing pressure have been considered as process parameters for each set of experimentation. Furthermore, the range of the process parameters have been optimised by three different MCDM techniques and is followed by validation by performing experiments.

To investigate the influences of various process parameters, which have been mentioned in above paragraph on different performance criteria while performing EDM process on ceramics, tool diameter of 1mm and workpiece of Alumina (40mm × 40mm × 5mm) have been chosen for experimentation. A copper adhesive tape has been selected to be used as an assisted electrode. Many trial experiments have been carried out to find the range of peak current (Ip), pulse on-time (Ton) and flushing pressure. The other process parameters like duty ratio, gap voltage, work-time, lift-time, inter-electrode gap and machining depth have been kept constant during all the experiments. A tungsten carbide drill bit (WC) tool has been selected as the tool due to its high melting point, hardness, impact strength, high electrical conductivity and brittleness. The drill bit has been provided with flutes for proper passage of the chips and also proper flow of the dielectric. Alumina (Al_2O_3) of 5 mm thickness has been selected as the workpiece material since these ceramics have low conductivity, high melting point and poor machinability. Moreover these ceramics also attribute excellent mechanical and physical properties such as low density, high strength and hardness or chemical resistance due to which they have found their use in almost every aspect of life. Copper adhesive tape of thickness 0.025mm has been used as an assisting electrode because of its excellent electrical conductivity and being an adhesive tape it was easily applicable on the workpiece surface.

During trial experimentation with above mentioned tool of diameter 1mm, it was observed that the sparking occurs at the range of 0.5-40 A of current and 0.5 µs-3 s of pulse on time but above 4 A of peak current and 10µs of pulse on time the hole size and tool wear rate was found more in case of Alumina (Al_2O_3). At the range of 1-4 A of current and 3-10 µs of pulse on time, hole size was found to be more prominent. For this reason, it was decided to conduct the experiments at four different peak currents, four different pulse on time levels and four different flushing pressures *i.e* at 1A, 2A, 3A, 4A and 3µs, 5µs, 7.5µs, 10µs and 0kg/cm^2, 5 kg/cm^2, 10 kg/cm^2, 15 kg/cm^2 respectively.

Tool was connected to positive as well as negative terminal of power supply and these were referred as reverse polarity and direct polarity of the tool respectively. EDM oil and deionised water were considered as the dielectric medium for the trial experimentation.

Copper used as the assisted electrode provides the starting conducting layer to machine the ceramic surface forming the intrinsic conducting layer. This further breaks down the hydro carbons of EDM oil resulting from the high temoerature at the machined area which further helps in the machining. So EDM oil is more suitable as compared to deionised water for machining ceramics using EDM. After performing several trial experiments 6 layers of copper tape *i.e.* 0.150 mm was applied on both the ceramic workpieces to perform the experimentation.

The next step of experiment plan is to find out the feasibility of machining of both the Alumina (Al_2O_3) workpiece with EDM oil and deionised water as dielectric and to search out the significant effects of EDM parameters and its effective working range on the workpieces. To fulfill this the experiments will be performed varying one process at a time on both the workpieces seperately. The machined surface have been analysed using XRD and optical photograph.

4.2. Selection of Workpiece And Tool Electrode Material

The selection of the material of job sample and tool electrode in EDM is an important task because the machining performance totally depends on the combination of job and tool electrode. The common ceramic material like Alumina (Al_2O_3) due to its hardness in the sintered state make it difficult to machine with conventional cutting techniques. One approach for a solution is the use of electrical discharge machining (EDM). Due to the removal of material by thermal ablation, it is independent of the mechanical properties such as hardness, strength, and brittleness. Therefore considering the existing non-traditional machining processes EDM is considered as one of the best process to machine ceramics because of its simple and cost effective nature. The strength of the tool should be high due to the various pressures acting on the tool and tool tip. A tungsten carbide (WC) tool exhibits more strength and hardness that pure tungsten, moreover it has high melting point as well which is one of the characteristics a tool should posses. It should also allow proper passage of the chips removes during machining and also allow smooth flow of dielectric for good machining efficiency. So a tungsten carbide (WC) drill bit tool has been chosen as the tool material.

4.2.1. Properties of workpiece and tool material

The selection of job and tool combination depends on the various properties of workpiece and tool materials. The physical, thermal, electrical and mechanical properties of the Alumina (Al_2O_3) and tunsten carbide (WC) are shown in Table 4.1.

Table 4.1. Properties of job sample and tool electrode material

Properties	Alumina (Al_2O_3)	Tunsten carbide (WC)
Density (g/cm3)	≥ 3.85	15.63
Melting Point (ºC)	2040	2870
Boiling point (ºC)	2980	6000
Thermal conductivity ($W.m^{-1}·k^{-1}$) at 25ºC	35	110
Electrical resistivity (Ω.cm)	1×10^{14}	0.2×10^{-4}
Modulus of Elasticity (GPa)	375	≥ 600
Poissons ratio	0.22	0.31
Hardness (kg/mm^2)	1440	2400
Coefficient of thermal expansion ($ºC^{-1}$)	8.4×10^{-6}	6×10^{-6}

4.2.2. Applications of Workpiece Material

Alumina is commonly termed as aluminum oxide which synthetically produces aluminum oxide. It is a chemical compound comprising of oxygen and aluminum. It is a colorless crystalline substance that is found naturally in the variety of forms namely sapphire and ruby. Unlike standard ceramics that tend to be brittle and hard, Alumina has excellent wear resistance and strength, and comes with a flexibility which is far better than those of other technical ceramics. They are mostly used in a production of aluminum metal. Alumina are widely used in electronic substrates, thread and wire guides, seal rings, ballistic armor, thermometry sensors, grinding media, furnace liner tubes, high voltage insulators, laboratory instrumentary tubes. Various formulation of glass consists of aluminum oxide as an ingredient. It is used in purification that is the removal of water from gas streams. They are employed in high-performance applications. They are broadly used as an abrasive. Various sandpaper makes use of aluminum oxide crystals.

Alumina is used in a wide range of applications, such as precision ball valve (seats and balls), valves and impellors, pump seals, oxygen sensors, high density grinding media, fuel cell membranes, thread guides, medical prostheses, cutting blades, gears, metal forming, radio frequency heating susceptors, metrology components, bearings, bushes and drive shafts

4.3. Selection of Assisting Electrode Material

Assisting electrode (AE) provides the initial electrical contact during EDM of non-conductive ceramics and hence the process would not be possible without it. Once the assisted electrode is machined, the electrical contact at the region of machining is provided and sustained by the intrinsic conductive layer (ICL). Hence, AE and ICL are the most important aspect during the EDM process of non-conductive ceramics.

The AE can be made up of material that is conductive and can be applied on top of a non-conductive ceramic. Since metals are conductive, they can be used as an AE for the EDM process. A metal foil can be attached on top of the non conductive ceramics in various ways. One simple way would be to attach a metal foil on top of the non-conductive ceramic mechanically. The major advantage of this methods is its simplicity. The major disadvantage of simply clamping a metal foil on the non-conductive ceramic is the lack of a direct contact between the metal and the non-conductive ceramic. To fulfill all the above criterion adhesive copper tape was selected as an assisting electrode, since copper has good electrical conductive and being adhesive it could be easily applied on the ceramic workpiece mechanically. Therefore initially a layer connecting the copper and ceramic will be formed. The EDM process ceases to proceed in case the layer fails to form. Since there is no direct contact between the metal foil and the ceramic, the time required to form the ICL is very high.

4.4. Experimental Conditions and Procedure

After setting the objectives of the experiments, the present experimental conditions have been made to analyse the effects of various process parameters on the various characteristics of EDM while machining non-conductive ceramic material i.e. Alumina (Al_2O_3) using assisted electrode method using copper adhesive tape as an assisting electrode. The constant machining parameters selected for investigations are listed below in Table 4.2.

Table 4.2. Constant machining parameters for machining Alumina using EDM

Work condition	Description
Dielectric	EDM oil
Duty factor (%)	10
Machining depth	1.2 mm
Work time (spark time)	2 sec
Lift time	0.5 sec
Gap voltage	50 V

The experiments have been conducted at above mentioned conditions shown in Table according to the following procedures. Procedural steps for the fulfillment of the present research works are enlisted below:

(i) Firstly, the machining chamber is cleaned properly with pure distilled water.

(ii) Before machining, the weight of each workpiece and tool is measured by METTELER TOLLEDO weighing machine (LC of 1×10^{-2} mg).

(iii) The diameter of each tool is recorded with the help of LEICA microscope at magnification of 10X (LC of 1×10^{-3} µm).

(iv) The workpiece surface is cleaned using acetone and copper tape is mechanically applied as assisting electrode avoiding any air gap.

(v) The workpiece is clamped just below the tool tip and kept just 2 mm above the upper level of dielectric, cleaned carefully with acetone.

(vi) Main power is switched on and the inter-electrode gap (5 µm) is automatically maintained by the ATPS switch of control panel.

(vii) The current tool position is set at 0-0-0 level at 'DRO' mode and followed by set the various process parameters are set at the 'EDM' mode in the control panel.

(viii) The machining operation was performed according to the experimental plan and the reading of machining time is recorded by a digital stop watch.

(ix) After the machining operation, the main power is switched off and the workpiece was removed, dried and cleaned carefully with acetone. The weight of the job was measured with METTELER TOLLEDO weighing machine (LC of 1×10^{-2}mg). The entrance and exit diameters of machined micro-holes were measured at magnification of 20X in LEICA microscope (LC of 1×10^{-3} µm).

(x) Composition of tool and the workpiece material after machining is measured by X-ray diffraction technique with the help of RIGUTA-ULTIMA (at 40 kV, 30 mA).

(xi) Finally the optical photographs of the machined surfaces of Alumina has been taken under LEICA optical measuring microscope.

4.5. Evaluation of the Performances Characteristics

After conducting the experiments the various EDM performances characteristics have been calculated as discussed below:

In EDM, material is removed not only on the workpiece but also from the tool and size and shape of hole is just a replica of that tool. Therefore, in this research work three EDM performance characteristics, i.e., material removal rate (MRR), tool wear rate (TWR), and over cut (OC) have been considered. The method of calculating these performance criteria are described as follows

(i) Material Removal Rate (MRR)

Material removal rate in EDM is defined as the amount of material removed from the work piece per unit time and usually expressed in g/min as given below in the Eq.1. In this work it has been calculated by weight loss of the workpiece per unit time by METTELER TOLLEDO weighing machine (Least Count of 1×10^{-2}mg).

$$MRR= (W_{bw} - W_{aw})/t, \qquad g/min \qquad \text{(Eq.7)}$$

Where,W_{bw} is the weight of the workpiece before machining, g; W_{aw} is the weight of the workpiece after machining, g and t is the time taken for machining.

(ii) Tool Wear Rate (TWR)

Tool wear rate in EDM is defined as the amount of material eroded from the tool per unit time and usually expressed in g/min as given below in the Eq.2. It this work it has been calculated by weight reduction of the tool taking weight of it before and after machining per unit time by METTELER TOLLEDO weighing machine (Least Count of 1×10^{-2} mg).

$$TWR= (W_{bt} - W_{at})/t, \qquad g/min \qquad \text{(Eq.8)}$$

Where, W_{bt} is the weight of the tool before machining, in g; W_{at} is the weight of the tool after machining, in g and t is the time taken for machining.

(iii) Overcut (OC)

It is the extra material removed by the tool that exceeds its diameter. It is the difference between the diameter of the hole and the tool diameter obtained by LEICA microscope at magnification of 10X (Least Count of 1×10-3 µm) as shown in Fig.4.1. The overcut is calculated according to the equation given below the figure

$$OC = \frac{\sum Di}{N} - d_T \qquad \text{(Eq.9)}$$

Where, D_i is the hole diameter at i^{th} section, mm; d_T is the tool diameter, mm and N is the number of measurements.

5. OPTIMIZATION BASED ON MCDM TECHNIQUES

Multiple criteria decision making (MCDM) is the process of selecting the best alternative from a set of feasible alternatives considering multiple conflicting criteria. In precise terms criteria are considered to be 'strictly' conflicting if the increase in satisfaction of one results in a decrease in satisfaction of the other. An MCDM process always contains at least two alternatives and two conflicting criteria. Several useful tools for solving of MCDM problems are:

(i) Simple Additive Weighting method (SAW)
(ii) Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)
(iii) Multi Objective Optimization Ratio Analysis(MOORA)
(iv) Analytical Hierarchy Method (AHP)
(v)Analytical Network Method ANP etc.

MCDM are divided two broad categories: Multiple Attribute Decision Making (MADM) and Multiple Objective Decision Making (MODM). Differences between them are listed below which helps to choose which technique can be used in the present analysis. Table 5.1 shows the comparison between both the techniques.

Table 5.1. Differences between MADM and MODM technique

Subject	**MADM**	**MODM**
Criteria	Different attribute	Objective function
Objective	Implicit	Explicit
Attribute	Explicit	Implicit
Constraint	Inherent	Mathematical form
Alternatives	Finite number	Infinite number
Usage	Selection or Evaluation	Design

Multi Attribute Decision Making problems are considered in this situation, where several objectives or attributes or the criteria’s are conflicting and explicit in nature. During decision making through MADM always there is a restriction. MADM constraints are very much inherent and there is no explicit mathematical form. Thus the process involves the selection of the alternatives, which are predefined and finite in number. So the decision space considers the finite number of point. In MADM, the criteria's are commensurable in nature because they are measured in different units. MADM process considers normalization technique as the units of different criteria are in different scale. MADM also has its application where the criteria's are conflicting in nature. From the above discussion it can be concluded that the problem in the present research work should be solved by MADM technique [47, 48, 49]. In this research work, three techniques e.g. Simple Additive Weighting method (SAW), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Multi Objective Optimization Ratio Analysis (MOORA) have been considered to optimize the process parameters during EDM of ceramic. The steps involved for the above mentioned techniques are discussed hereunder:

(i) Simple Additive Weighting (SAW)

Step 1: Formation of decision matrix: Criterion outcomes of decision alternatives can be collected in a table called Decision Matrix comprised of a set of columns and rows. The matrix rows represent decision alternatives, with matrix columns representing criteria. A value found at the intersection of row and column in the matrix represents a criterion outcome - a measured or predicted performance of a decision alternative on a criterion. The decision matrix is a central structure of the MCDA/MCDM since it contains the data for comparison of decision alternatives.

$$\begin{array}{c} \\ X = \end{array} \begin{array}{c} \\ A_1 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{array} \begin{array}{c} \mathbf{C_1} \quad\quad \mathbf{C_J} \quad\quad \mathbf{C_n} \\ \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix} \end{array}$$

x_{ij} is the performance rating of alternative ***i*** with respect to criterion ***j***,

A_j is ith alternative, C_j is the jth criterion

Step 2 Formation of Weight Matrix

Different importance weights to various criteria may be awarded by the decision makers. These importance weights forms the weight as follows.

$$W = [W_1 \cdots W_j \ldots W_n] \quad \text{(Eq.10)}$$

Step 3 Normalization of performance rating

Units and dimensions of performance ratings of columns under criteria differ. For the purpose of comparison, these performance ratings are converted into dimensionless units by normalization using following equations

$$\bar{x}_{ij} = \frac{x_{ij}}{\max_i(x_{ij})} \text{ for benefit criteria } \boldsymbol{j} \quad \text{(Eq.11)}$$

$$\bar{x}_{ij} = \frac{\min_i(x_{ij})}{x_{ij}} \text{ for non-benefit criteria } \boldsymbol{j} \quad \text{(Eq.12)}$$

Normalized decision matrix

$$\bar{X} = \begin{matrix} A_1 \\ \vdots \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{bmatrix} \bar{x}_{11} \cdots & \ldots \bar{x}_{1j} \ldots & \bar{x}_{1n} \\ \vdots & \vdots & \vdots \\ \bar{x}_{i1} \ldots & \ldots \bar{x}_{ij} \ldots & \bar{x}_{in} \\ \vdots & \vdots & \vdots \\ \bar{x}_{m1} & \bar{x}_{mj} & \bar{x}_{mn} \end{bmatrix}_{m \times n}$$

Step 4 composite score: Computation of composite score (CS_i) for alternative *i*

$$CS_i = \sum_{j=1}^{n} \left(\bar{w}_j * \bar{x}_{ij}\right) \quad \text{(Eq.13)}$$

Step 5 Ranking and selection of best alternative: Ranking of products in descending order of composite scores (CS_i).

(ii) Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS is an evaluation method that is often used to solve MCDM problems. It has a number of application in practice, such as comparison of company performances, financial ratio performance within a specific industry and financial investment in advanced manufacturing systems, etc. However, there are also some limits to it. So far, the work on how to improve original TOPSIS method has mainly emphasized on improving the weight to sensitize the *R* value. Besides, there has also been improvement on formula of the *R* value, such as the 'Miqiezhi' method. Because of the complexity of evaluation problems, a better and simpler method is required to understand the inherent relationship between the *R* value and alternative evaluation. In this report, a novel, modified TOPSIS (M-TOPSIS) method is described as a process of calculating the distance between the alternatives and the reference points in the *D*+ *D*−-plane and constructing the *R* value to evaluate quality of alternative.

Step1. All the original criteria receive tendency treatment. We usually transform the non benificial criteria into benefit criteria, which is shown in detail as follows;

(i) The reciprocal ratio method ($X_{ij}= 1/X_{ij}$), refers to the absolute criteria;

(ii) The difference method ($X = 1 - X_{ij}$), refers to the relative criteria.

After tendency treatment, construct a matrix

$$X' = [X']_{n\times m},\ i = 1,2,3 \ldots \ldots \ldots \ldots \ldots \ldots \ldots m \qquad \text{(Eq.14)}$$

Construction of weighted matrix depends upon the weight value assigned to the different criteria.The summation of the all weight must be equal to one. In TOPSIS method the assigned weighted values are 0.3340, 0.3330 and 0.3330. These weighted values have been assigned using entropy method.

Step2. Calculate the normalized decision matrix A. The normalized value a_{ij} is calculated as

$$A = [a_{ij}]_{n\times m}, a_{ij} = \frac{X'_{ij}}{\sqrt{\sum_{i=1}^{n}\left(X'_{ij}\right)^2}} \quad i = 1,2,3 \quad \ldots \ldots \ldots \ldots n\ \&\ j=1, 2, 3 \quad \ldots\ldots\ldots\ldots m$$

Step3. Determine the positive ideal and negative ideal solution from the matrix A.

$$A^{+} = (a_{i1}{}^{+}, a_{i2}{}^{+}, \dots \dots \dots \dots \dots \dots\ a_{im}{}^{+}, a_{ij}{}^{+}) = \max\left(a_{ij}\right), \qquad j = 1,2, \dots \dots \dots .. m$$

$$A^{-} = (a_{i1}{}^{-+}, a_{i2}{}^{-}, \dots \dots \dots \dots \dots \dots\ a_{im}{}^{-}, a_{ij}{}^{-}) = \min\left(a_{ij}\right), \qquad j = 1,2, \dots \dots \dots .. m$$

Step4. Calculate the separation measures, using the n-dimensional Euclidean distance. The separation of each alternative from the positive ideal solution is given as:

$$D_i^{+} = \sqrt{\sum_{j=1}^{m} W_j (a_{ij}{}^{+} - a_{ij})^2} \qquad \text{(Eq.15)}$$

Similarly, the separation from the negative ideal solution is given as

$$D_i^{-} = \sqrt{\sum_{j=1}^{m} W_j (a_{ij}{}^{-} - a_{ij})^2} \qquad \text{(Eq.16)}$$

Step5. For each alternative, calculate the closeness index R_i as:

$$R_i = \frac{D_i^{-}}{D_i^{-} + D_i^{+}} \qquad \text{(Eq.17)}$$

Step6. Rank attributes in increasing order according to the closeness index value.

The attributes having highest value of closeness index is most preferable and the other attributes are taken in the decreasing order of their closeness index value.

Table 5.3 is the decision matrix in this problem and above sequential operations are performed on the basis of decision matrix to obtain the closeness index value for each and every alternative. Then the Closeness index values are arranged in chronological order to get the best available alternative. The maximum closeness index value indicates the best alternative and lowest closeness index indicates the worst.

(iii) Multi Objective Optimization Ratio Analysis (MOORA)

The MOORA method which was introduced by Brauers which is such a multi objective optimization technique that can be successfully applied to solve various types of MCDM problems. The Algorithms of MOORA method are discussed as follows:

The MOORA method starts with a matrix of responses (performance measures) of different alternatives on different criteria (objectives or attributes). The matrix is shown below

$$X = \begin{array}{c} \\ A_1 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & \cdots & C_j & \cdots & C_n \end{array} \\ \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix} \end{array}$$

Where, x_{ij} is the performance rating (response) to the *i*th alternative (A_i) under *j*th criterion (C_j) *m* is the number of alternatives and *n* is the number of criteria.

The MOORA method employs a ratio system in which each response of an alternative on an attribute (criterion) is compared to a denominator. The denominator is a representative for all alternatives concerning that attribute. The square root of the sum of squares of each alternative per objective is the best one for the denominator which is given below.

$$x_{ij}^* = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} \left(x_{ij}^2\right)}} \quad \text{(Eq.18)}$$

x_{ij}^* is normalized value of response *i* with respect to attribute *j*. In the current research work, the maximum score under each attribute has also been used as the denominator of the ratio system and an effort has been made to exhibit that this ratio system is also suitable for finding the optimal solution. The following ratio system is the second best for normalization process in MOORA.

$$x_{ij}^* = \frac{x_{ij}}{\max_i \left(x_{ij}\right)} \quad \text{(Eq.19)}$$

For the computation of normalized response using the above Eq.18, first the maximum score under each attribute is found. Then all the scores under certain attribute irrespective of benefit or non-benefit are divided by the concerned maximum score using Eq.19, x_{ij}^* is a dimensionless quantity in the interval [0,1] representing the normalized score of alternative *i* on attribute *j*. However, sometimes the interval could be [-1; 1]. For example in the case of productivity growth of some factories, industries, sectors, regions or countries may be negative instead of positive thus the interval becomes [-1;1].

For multi-objective optimization these normalized performances are added in case of maximization and subtracted in case of minimization. Then the optimization problem becomes:

$$y_i^* = \sum_{j=1}^{g} x_{ij}^* - \sum_{j=g+1}^{n} x_{ij}^* \qquad \text{(Eq.20)}$$

Where *g* is the number of benefit criteria to be maximized and *(n-g)* is the number of non-benefit criteria to be minimized. y_i^* is final score of i^{th} alternative with respect to all the attributes. In the above case it is assumed that all the attributes are of same importance.

$$y_i^* = \sum_{j=1}^{g} w_j * x_{ij}^* - \sum_{j=g+1}^{n} w_j * x_{ij}^* \qquad \text{(Eq.21)}$$

Where, w_j^* is the weight of jth attribute (criterion), which can be evaluated using any well-known approach either AHP or Entropy method. The value of y_i^* may be positive, negative or zero. These y_i^* values are arranged in descending order. The best alternative is one which is associated with highest y_i^* value and the worst alternative is one which is associated with the lowest y_i^* value.

5.1. Finding Best Set of Parametric Combination Utilizing Different Multicriteria Decision Making Technique

After the preliminary experimentation, most influencing parameters need to be selected. Experiments will be conducted by keeping one parameter fixed at a time and accordingly the responses i.e. material removal rate (MRR), tool wear rate (TWR) and overcut (OC) will be recorded. From the obtained performance criteria values for every parametric combination, the choice of best set of parametric combination will be made.

Multi criteria decision making (MCDM) problem involves several objective functions within a predetermined set of constraints. With respect to the relation defined within the criteria it can be classified in to two groups, multi attribute decision making (MADM) and multi objective decision making (MODM). This type of decision making involves multiple factor such as identification, consideration and analysis of viability. MCDM is one of the most widely used decision making methodology as that follows the analysis of several criteria simultaneously for making the choice sustainable. In this research MCDM has been used for making choice of best parametric combination. Overviews of most influencing EDM process parameters and their effect on various responses have been studied in the preliminary experimentation. Experimentation will be done by varying one process parameter at a time and a total of 10 experiments will be performed to find out the best set of process parametric combination which is responsible for improving material removal rate (MRR) with lowest tool wear rate (TWR) and overcut (OC).

5.2. Problem Definition and Formation of Decision Matrix

In the present study, decision needs to be made by selecting the best alternative set of process parameter value from the ten set of feasible alternatives considering multiple conflicting criterion. Criteria are considered strictly conflicting if the increase in satisfaction of one result is a decrease in satisfaction of the other. Some very well known MADM methodologies are AHP, TOPSIS, VIKOR, PROMETHEE, SAW, MOORA, ANP etc. In the present research work the selection of best set of parametric combination will be done by TOPSIS, MOORA and SAW method due to their simplicity, adaptability, applicability in this research work.

Problem should be defined in a proper way before starting the selection procedure. In this study, out of total ten set of parametric combinations of the alternatives, the best alternative should be selected. In the research work, three responses i.e. material removal rate (MRR), tool wear rate (TWR) and overcut (OC) have been considered as the conflicting criterion. Out of this material removal rate (MRR) is beneficial criteria because it's higher value is desirable whereas tool wear rate (TWR) and overcut (OC) are considered as non beneficial criteria because their lower values are desirable. Another important factor is to assign weight to the specific criteria. Smaller the weight values for a particular criterion bigger the variation extent of assessment value of that particular criterion and vice versa. It means the more amount of information provided; the greater role of a criteria is expected as its weight value is higher. In this study, all the three criteria is directly related to the dimensional and profile accuracy of the machining profile. Therefore for all operations performed similar weight is given to all the criteria.

Table 5.2. Showing different criteria for problem formulation

Benificial criteria (higher the better value)	Material removal rate (MRR)
Non benificial criteria (lower the better value)	Tool wear rate (TWR)
	Overcut (OC)

The objective of this analysis is to assess the performance characteristics of the machined profile while machining with different alternative parametric combination. Here counselling of the above three criteria has been done to select the best alternative. In this study SAW, TOPSIS, MOORA methods have been used for finding the best alternative.

Firstly, the formation of decision matrix is required to conduct further operation as per the particular MCDM method is concerned. Decision matrix has been formed by measured value of the responses as obtained after conducting EDM experiments with the help of alternative set of parametric combinations i.e. the ten set of experimental conditions with peak current (I_p), on time (T_{on}) and flushing pressure combinations as shown in the Table 5.3.

Table 5.3 Decision Matrix for different MADM techniques

				Higher the better	Lower the better	
Exp. no.	Peak current (I_p) A	On time (T_{on}) µs	Flushing pressure Kg/cm^2	Material removal rate (MRR)	Tool wear rate (TWR)	Overcut (OC)
1	1	3	5	0.000062023	0.0000405063	0.2516880
2	2	3	5	0.000046158	0.0000357143	0.4139190
3	3	3	5	0.0000261905	0.0000138095	0.5147880
4	4	3	5	0.000022439	0.00000146341	0.7896380
5	1	3	0	0.000118000	0.000045000	0.6714110
6	1	3	10	0.000016000	0.0000200787	0.2616880
7	1	3	15	0.000014000	0.0000192593	0.2270330
8	1	5	5	0.000126887	0.0000103774	0.2416880
9	1	7.5	5	0.0000647059	0.00000326797	0.2560600
10	1	10	5	0.000007500	0.0000015000	0.2880817

Further numerical calculations have been performed on the basis of decision matrix according to the various MADM techniques to evaluate the best alternatives or parametric combination as described in the subsequent sections.

6. EXPERIMENTAL RESULTS AND DISCUSSIONS

Experiments have been performed after varying process parameters e.g. peak current (I_p), on time (T_{on}) and flushing pressure and their effects on the responses i.e. material removal rate (MRR), tool wear rate (TWR) and overcut (OC) have been studied in the present research work. Various data have been obtained from the several measurements such as the magnitude of reduction in weight of the workpiece and tool, the machining time, the entry hole diameters of the blind holes in case of Alumina (Al_2O_3) workpiece respectively. A total of ten experiments have been performed and the obtained data has been used to analyse the performance characteristics.

6.1. Effect of the Coating Layer Thickness

Coating layer thickness has very significant effect on the machining of ceramic workpiece. In the present research work, trial experiments have been performed on the alumina workpeices by varying the coating layer thickness. Firstly, eight wraps of coating (i.e. 0.2 mm) on the alumina workpiece has been done for performing the trial experiments. It has been observed that with the increment of coating layer thickness more conductive thickness comes in contact with the spark, thus more heat is dissipated during EDM machining and once the copper layer has been machined, the tool reaches ceramic surface. So, it has been observed that with the increment of coating layer thickness more internal thermal stresses have been generated in the ceramic material which has lead to increase in thermal cracks on the ceramic workpiece.

After this it has also been observed that with the reduction in the coating layer thickness, thermal cracks on the ceramic workpiece have been reduced due to decrease in the thermal stresses. After several trial experiments with different coating layer thicknesses it has been observed that the optimum conditions have been achieved with wrapping of the six layers of copper foil i.e. 0.15 mm. This has lead to arrive at a conclusion that an optimum value of assisting electrode layer thickness leads to more stable machining in case of ceramic materials. Thus it is needed to select an optimum thickness of the assisting electrode in order to perform machining on ceramics. Thus, in thus research work 0.15 mm of coating layer thickness has been chosen as the optimum coating layer thickness for the further research work.

6.2. Effect of Dielectric Fluids

Dielectric fluids play a very crucial role in case of EDM machining on ceramics. In the present research work, several trial experiments have been performed with two types dielectric i.e. deionised water and EDM oil. In the former case, it has been observed that EDM machining on ceramics is not suitable due to the non formation of carbon layer on the machined surface which is very much essential for carrying out the further machining. It has been observed that it can machine to the depth which is exactly the thickness of the assisting electrode. As the non-conducting surface of ceramic comes in contact with the tool the machining ceases. But in the case of EDM oil, due to the formation of carbon layer on the machined surface machining is possible upto the desired depth. In EDM oil there is dissociation of hydro-carbon taking place at the machining site and carbon gets deposited on the non-conducting workpeice. This carbon forms a pyrolitic carbon layer which assists further machining of ceramics. This carbon deposition is not possible in case of deionised water because of absence of hydro-carbon. Thus it can be concluded that hydro-carbon based EDM oil is the only option for machining of alumina. Hence, in this experimentation EDM oil has been selected as the dielectric fluid and performed further experiments.

6.3. Effect of Tool Materials

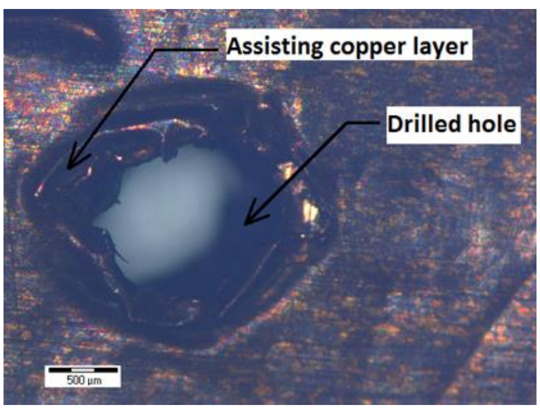
Trial experimentation have been performed with two types of electrode i.e. copper electrode with OD as 4 mm and ID as 3 mm and a solid tungsten carbide tool with diameter of 1 mm. In the first case, internal flushing of dielectric fluid has been incorporated and in the later case vertical flishing has been used. The former case has not given the desire result because of the two things. Firstly, because of internal flushing carbon deposition is not taking palce on the machined surface due to high pressure of flushing which ceases machining after certain depth. Secondly, the more tool diameter results in the heat energy getting unevenly dissipated in the alumina workpeice resulting in more HAZ. But in the latter case i.e. tungsten carbide the desired output has been obtained because of the desirable tool diameter with solid tool and vertical flushing. Because in case of solid tool more heat energy gets focussed on the machining area which results in the better machining with reduced HAZ. Hence, from this experimentation it can be concluded that tungsten carbide (WC) is the most suitable tool material for machining of alumina. Thus, in the present research work tungsten carbide tool has been used for further machining.

6.4. Effect of Tool Shape

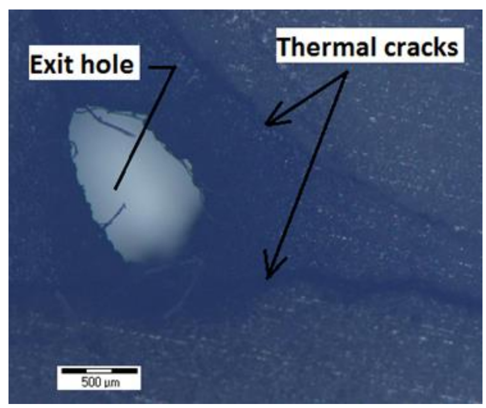
The shape of the tool also effects the machining. In present research trial experimentation has been performed using copper and tungsten carbide electrodes. The former is a cylindrical shaped hollow tool electrode while the latter is a drill bit with built in flutes on the periphery. It has been observed that during trial experiments better machining has been achieved with tungsten carbide drill bit tool because of its small diameter and the flutes that are present on its outer periphery. The presence of these flutes provide smooth passage for easy removal of the machined by-products and also helpful for smooth flow of the dielectric into the machining zone which is very much desirable in machining of ceramic. Since machined by-products get removed easily through these flutes so there is no possibility of machined by-products getting clogged in the machining area, which leads to smooth machining. Thus it can be concluded that tungsten carbide drill bit is best suited tool electrode for machining of alumina by EDM. Hence for the further study, tungsten carbide drill bit has been chosen as the tool electrode.

6.5. Effect of Workpiece Thickness

During machining of alumina by EDM it has been observed that thickness of the workpeice plays vital role in non-conducting ceramics. In trial experimentation, Alumina (Al_2O_3) workpiece of two different thickness i.e. 5 mm and 1 mm have been chosen. Blind holes have been machined in 5 mm thickness workpiece and through holes have been machined in 1 mm thickness workpeice. It has been observed that 1 mm thick workpeice is not able to withstand the thermal stresses generated during EDM operation which results in cracks being generated in the exit side of the workpeice. As in EDM material is removed by thermal ablation thus it produces various three dimensional surface and subsurface defects. Thus, in 1 mm thickness workpiece thermal cracks gets easily propagated as shown in the Fig.6.1. On the contrary to this 5 mm thickness alumina workpeice can withstand the above mentioned surface and subsurface defects which results in no sign of thermal cracks in the machined surface. Due to this for further experimentation 5 mm thick alumina workpeice has been selected.



(a)



(b)

Fig.6.1. Thermal cracks propagated in the Alumina of 1 mm thickness

(a) Hole at the entry side of workpiece (b) Hole at the exit side of workpiece

6.6. Analysis on the Machining Performances during Machining of Alumina (Al_2O_3)

In the present research work the main aim is to study the influence of major process parameters e.g. peak current (I_p), on time (T_{on}) and flushing pressure on the machining responses e.g. the material removal rate (MRR) and minimize the tool wear rate (TWR) and overcut (OC). Therefore an suitable range of these process parameters i.e. peak current (I_p) (1A, 2A, 3A, 4A), on time (T_{on}) (3µs, 5µs, 7.5µs, 10µs) and flushing pressure (0kg/cm^2, 5 kg/cm^2, 10 kg/cm^2, 15 kg/cm^2) have been selected and the graphs have been plotted accordingly.

6.6.1. Effects of different process parameters on material removal rate (MRR)

(i) Peak current (Ip)

Peak current is one of the most impactful parameters when machining materials using EDM. But the principle of machining non-conductive ceramics is different from that of conductive materials. In case of conductive materials material removal rate increases with increase in peak current (I_p) because increase in peak current leads to more energy at the machining site resulting in higher material removal rate hence increased MRR. But contrary to this in case of non-conductive ceramics increasing peak current leads to decrease in material removal rate as observed in case of our experimentation. In Fig.6.2 graph between I_p and MRR shows the trend. There is a decrease in MRR beyond peak current (I_p) of 1 A because increasing peak current leads to more carbon deposition in the workpiece and on the tool, which produces a very sharp spark while machining and reducing the removal of material from ceramic.

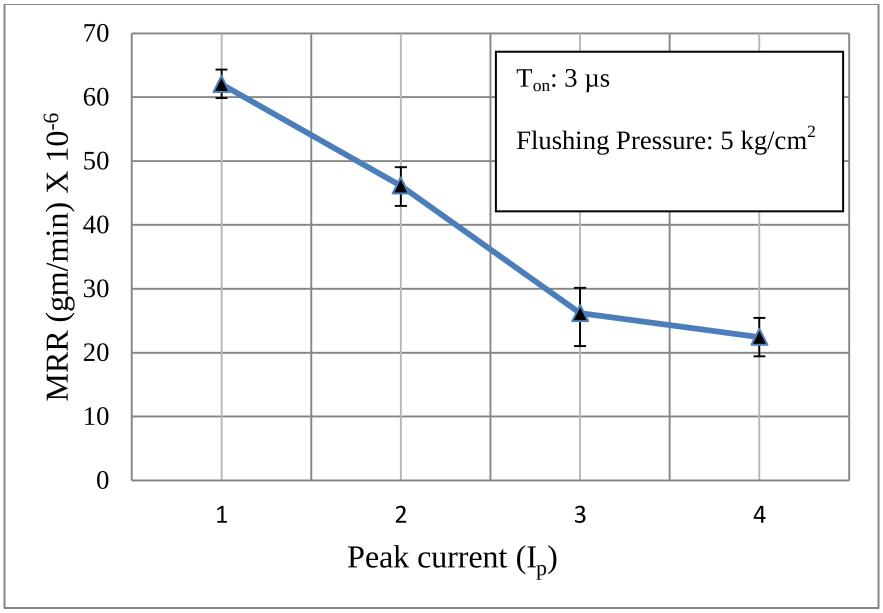


Fig.6.2. Variation of MRR vs Peak current

To investigate the carbon deposition on the Alumina (Al_2O_3) workpiece XRD analysis has been done of both the machined and unmachined surfaces as shown in Fig.6.4. The machined surface shows the deposition of pyrolitic carbon layer on the machined surface of alumina whereas as shown the Fig.6.3 the unmachined surface is free from carbon.

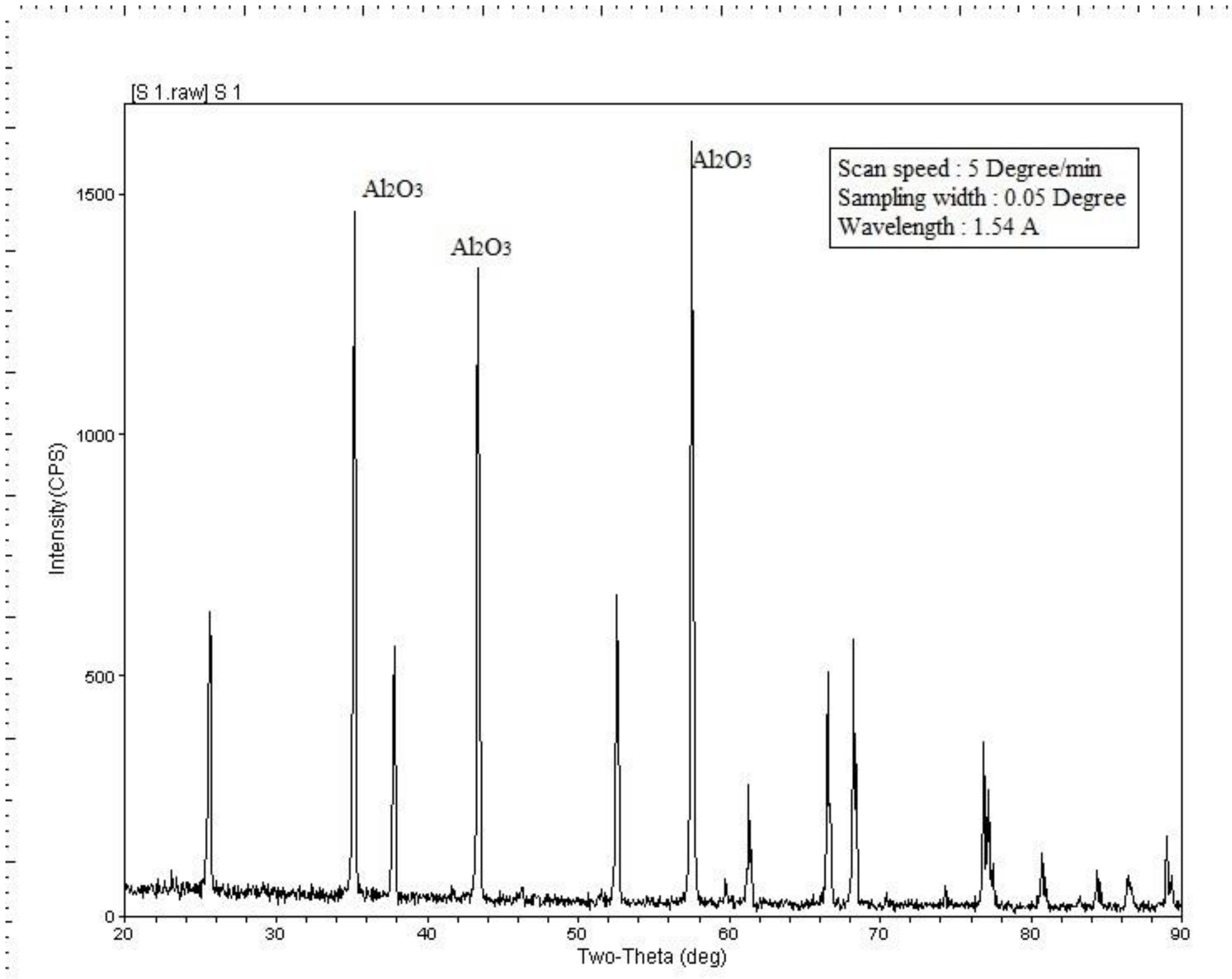


Fig.6.3. XRD analysis of the unmachined Al_2O_3 workpiece

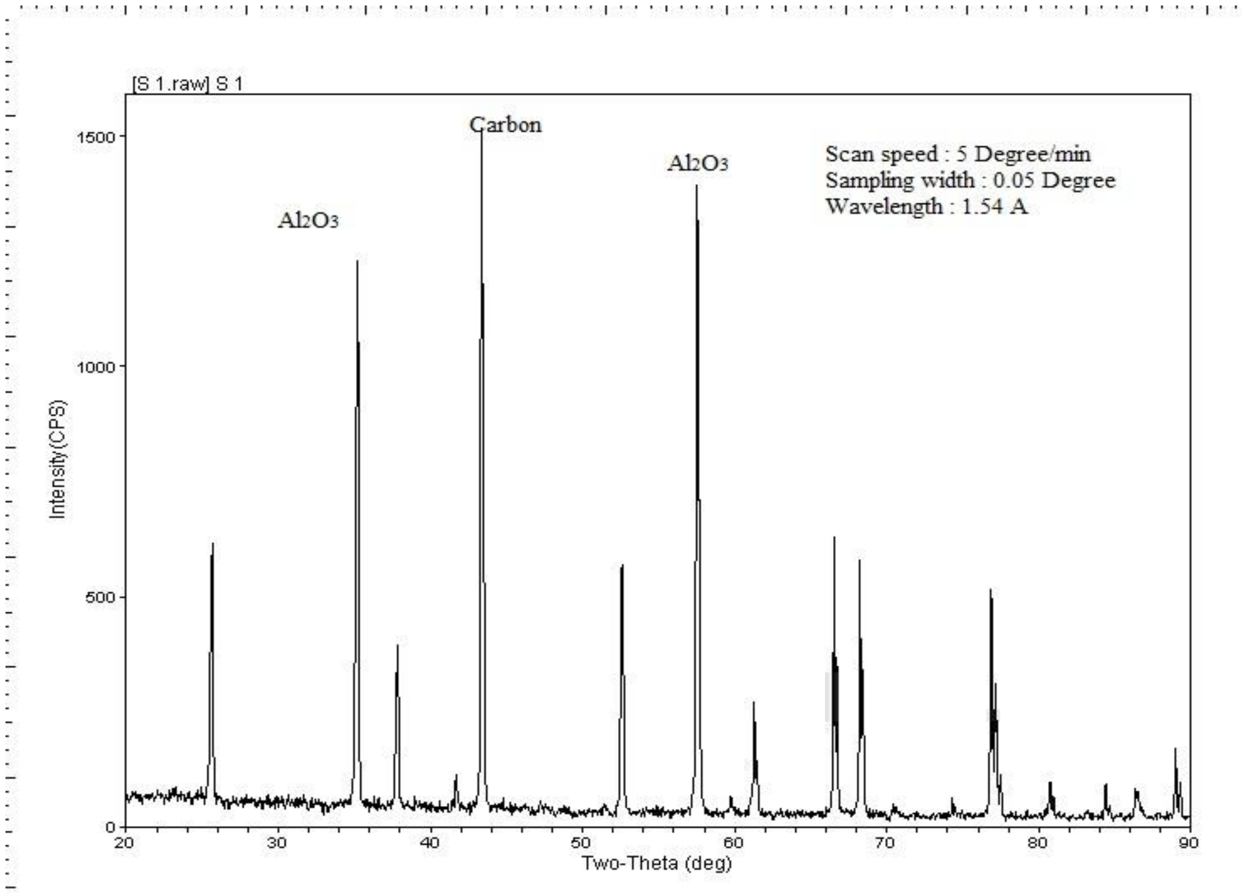


Fig.6.4. XRD analysis of the machined surface of Al_2O_3 workpiece

(ii) On time (Ton)

On time (T_{on}) is also one of the most important parameters in order to determine the material removal rate (MRR). Normally, in case of conductive materials increasing the on time leads to increase in material removal because of the increase in the thermal energy on the machining area but in case of ceramics and precisely alumina in present case MRR shows a decreasing trend with increase in on time (T_{on}). In Fig.6.5 the graph shows the trend. There is a decrease in the MRR with increase in the on time because in case of ceramics increasing on time leads to more carbon deposition on the workpeice thus making it difficult for the tool electrode to remove material. Hence, decreasing the material removal rate.

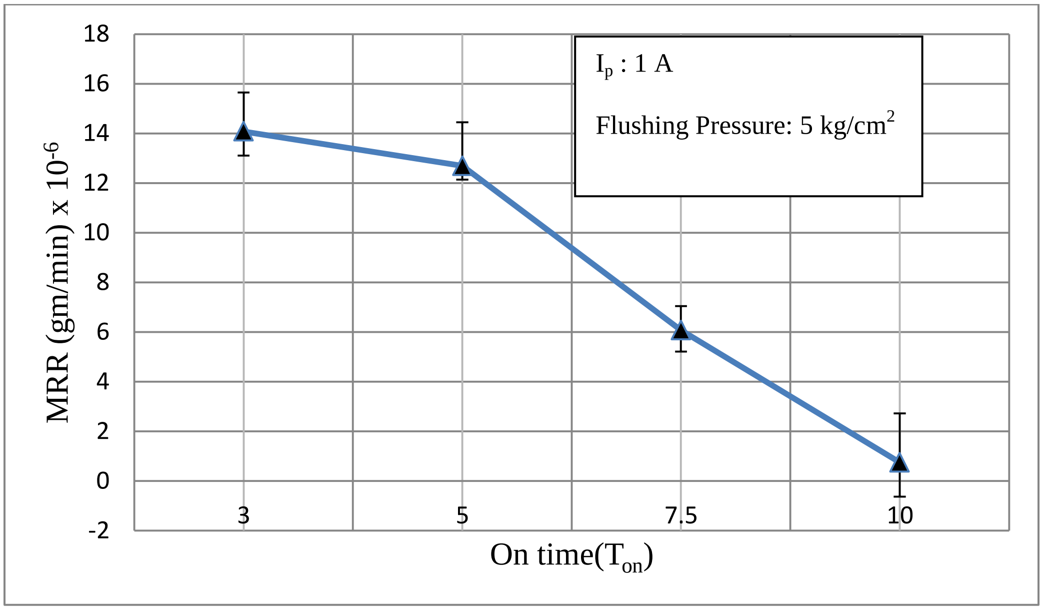


Fig.6.5. Variation of MRR vs On time

(iii)Flushing pressure

Flushing is the circlulation of the dielectric between the tool and the workpiece. Hence, increasing or decreasing the pressure plays a vital role on the material removal. Here in present experimentation it has been observed that there is a decreasing trend of MRR by increasing the flushing pressure. This is because increasing the flushing pressure continuously washes away the carbon layer being deposited on the workpeice during machining. This is the pyrolitic carbon layer which is deposited after the dissociation of the hydro-carbon oil due to th high temperature at the machining site. This deposited carbon layer assists the machining of ceramics once the intrinsic conductive layer has been machined during the assisted electrode method. Hence an optimum flushing pressure has to be maintained during machinig of ceramics using EDM to avoid washing away of deposited carbon. In Fig.6.6 the graph shows the trend of the flushing pressure vs material removal rate.

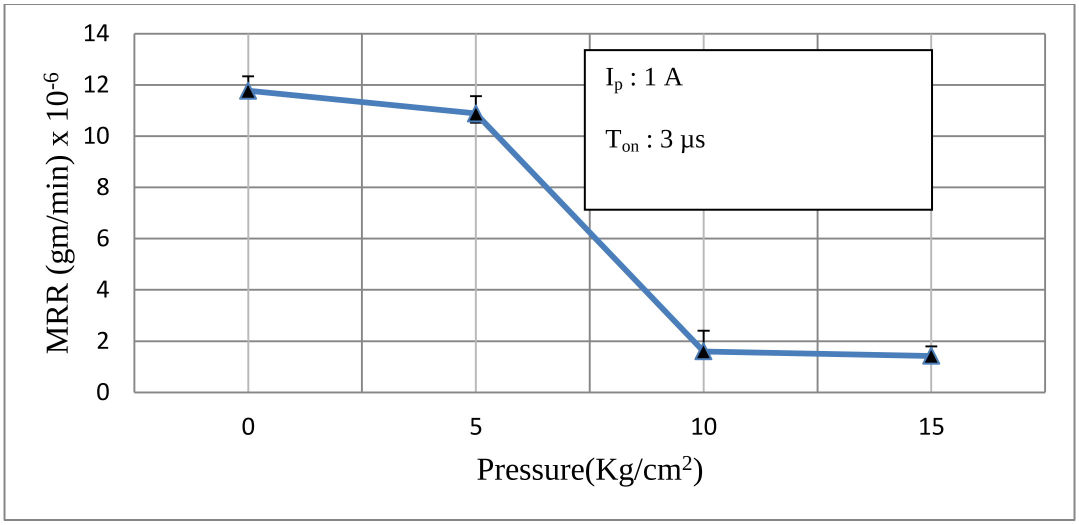


Fig.6.6. Variation of MRR vs flushing pressure

6.6.2. Effects of different process parameters on tool wear rate (TWR)

(i) Peak current (Ip)

The effect of peak current (I_p) on the tool wear rate is very significant. Generally in EDM increasing the peak current also increases the tool wear rate since more energy is concentrated on the machining surface generating more heat resulting in wear of the tool. But in case of ceramics (Al_2O_3 in this case) increasing the peak current results in more deposition of carbon on the tool tip surface, thus protecting the tool from getting wear out eventually increasing the tool wear life as shown in Fig.6.7.

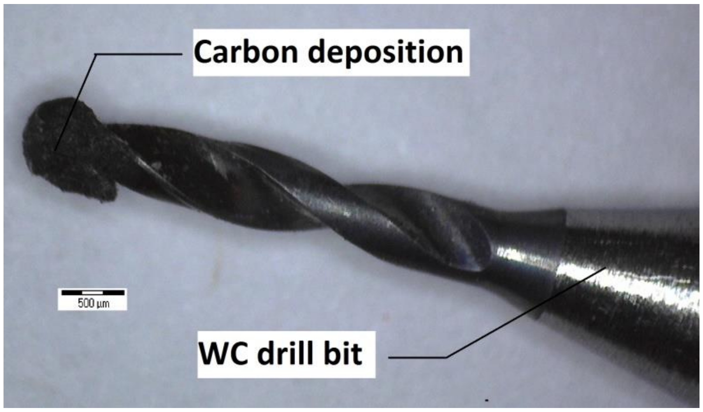


Fig.6.7. Deposition of carbon on the tool tip surface

Thus deposition of the carbon on the tool is helpful in increasing tool life and reducing tool wear. Hence increasing peak current decreases tool wear in case of non-conducting ceramics. In Fig.6.8 the graph shows the trend.

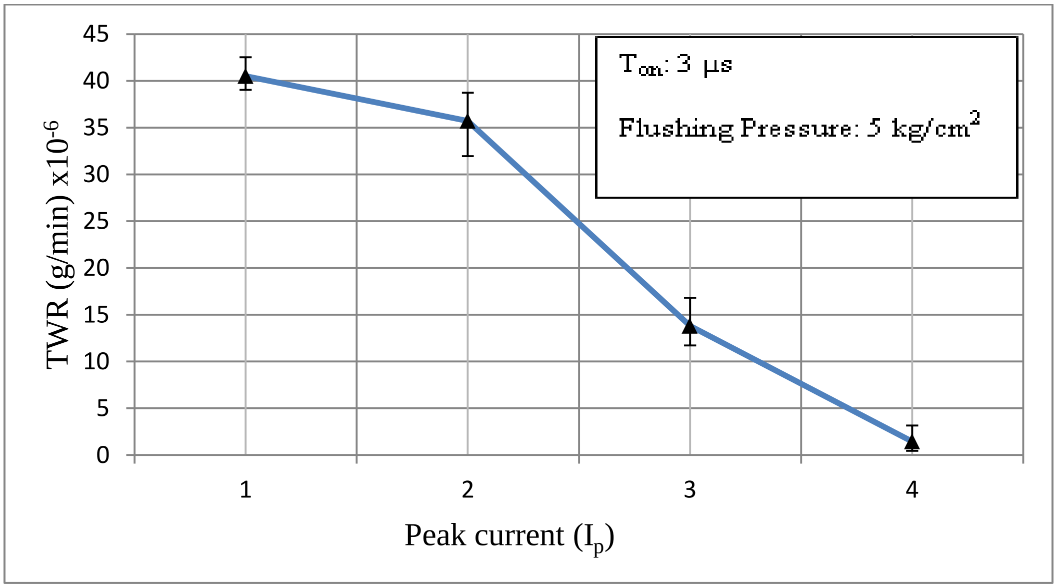


Fig.6.8. Variation of TWR vs Peak current

Further it is seen that since carbon deposition is taking place on the tool by increasing peak current, therefore a XRD report has been plotted in Fig.6.9 to show the presence of carbon on tool electrode, which prevents tool wear.

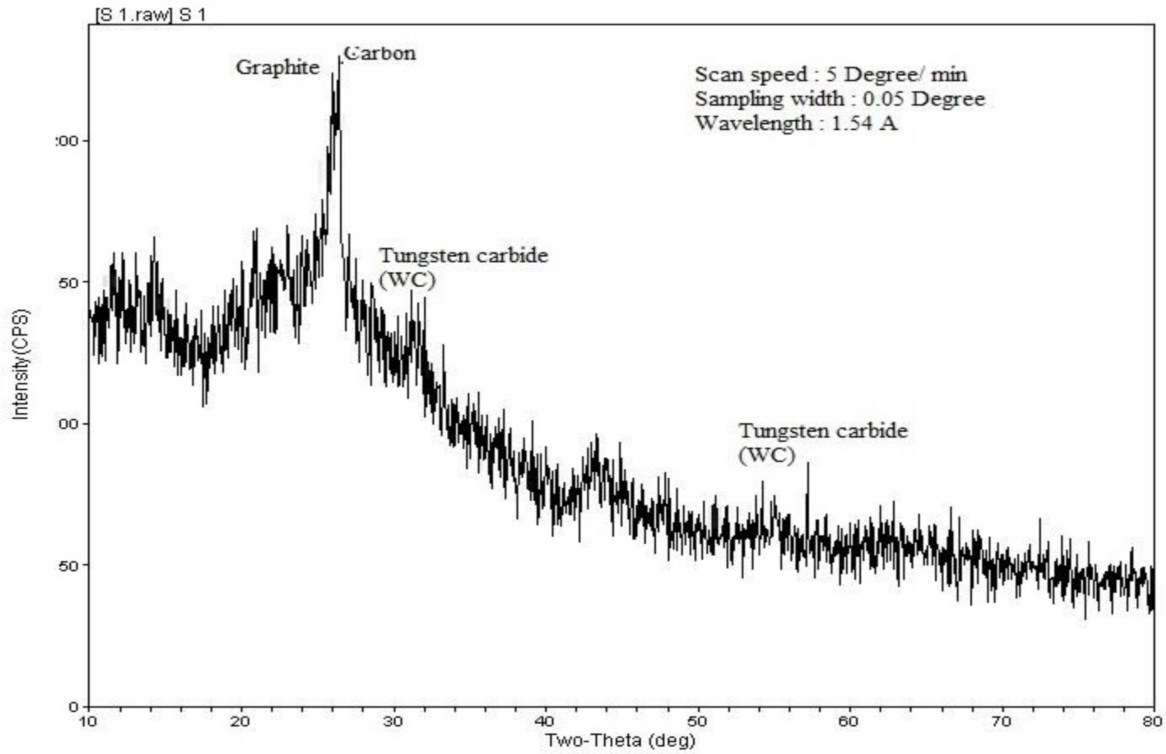


Fig.6.9. XRD analysis of the tungsten carbide tool after machining

(ii) On time (Ton)

Increasing on time leads to increase in tool wear rate in normal EDM process because increasing on time results in increase of energy on the machined area eventually increasing temperature which is unfavourable for the tool electrode material thus, resulting in the increase in tool wear rate. But in case on non-conducting materials (ZrO_2 in our case) the behaviour is entirely reverse. Increasing the on time leads to increase in the heat thus resulting in more dissociation of hydro-carbon dielectric, thus forming carbon on the tool electrode material. The carbon deposited on the tool surface increases the tool life and thus reduces the tool wear rate. In Fig.6.10 graph shows the trend of on time vs tool wear rate

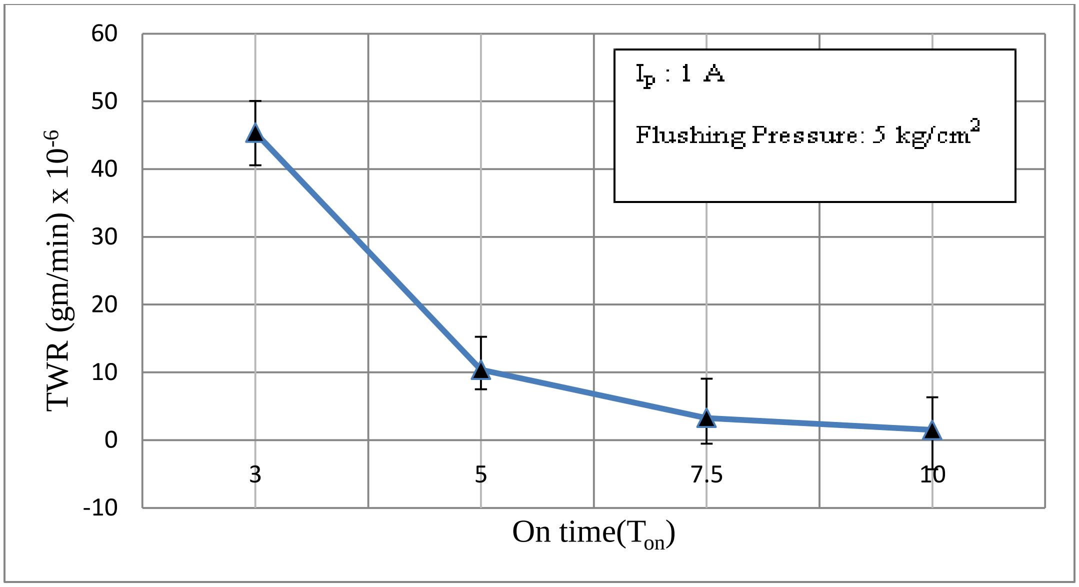


Fig.6.10. Variation of TWR vs On time

(iii)Flushing pressure

The flushing pressure shows an increasing trend because increasing flushing pressure removes the carbon deposited on the tool thus exposing tool to the high temperature and hence increasing the tool wear rate. In Fig.6.11 graph shows the trend

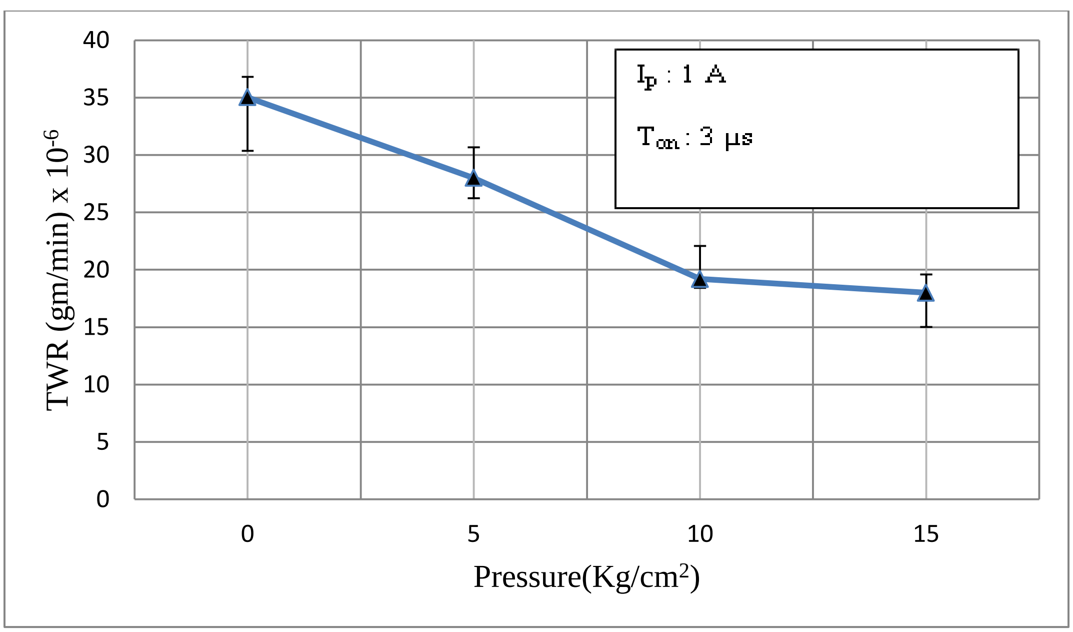


Fig.6.11. Variation of TWR vs Flushing pressure

6.6.3. Effects of different process parameters on overcut (OC)

(i) Peak current (Ip)

Increasing peak current results in the more heat dissipation on the machining surface, resulting more heat getting distributed. This leads to an increase in the HAZ of the machined area and increased overcut. Hence overcut (OC) shows an increasing trend with the peak current. In Fig.6.12 graph shows the trend

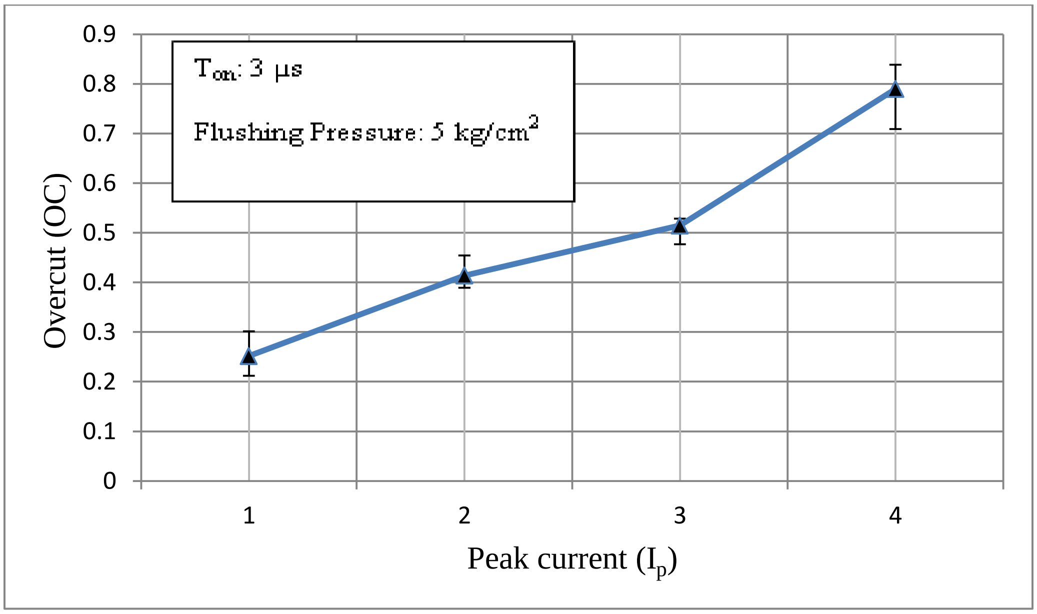


Fig.6.12. Variation of Overcut(OC) vs Peak current

(ii) On time (Ton)

Increasing on time results in the more heat concentration thus increasing the HAZ of the machined area. Hence overcut (OC) shows an increasing trend with the peak current. So basically on time has the same offect on the over cut (OC) as that of the peak current. In Fig.6.13 graph shows the trend

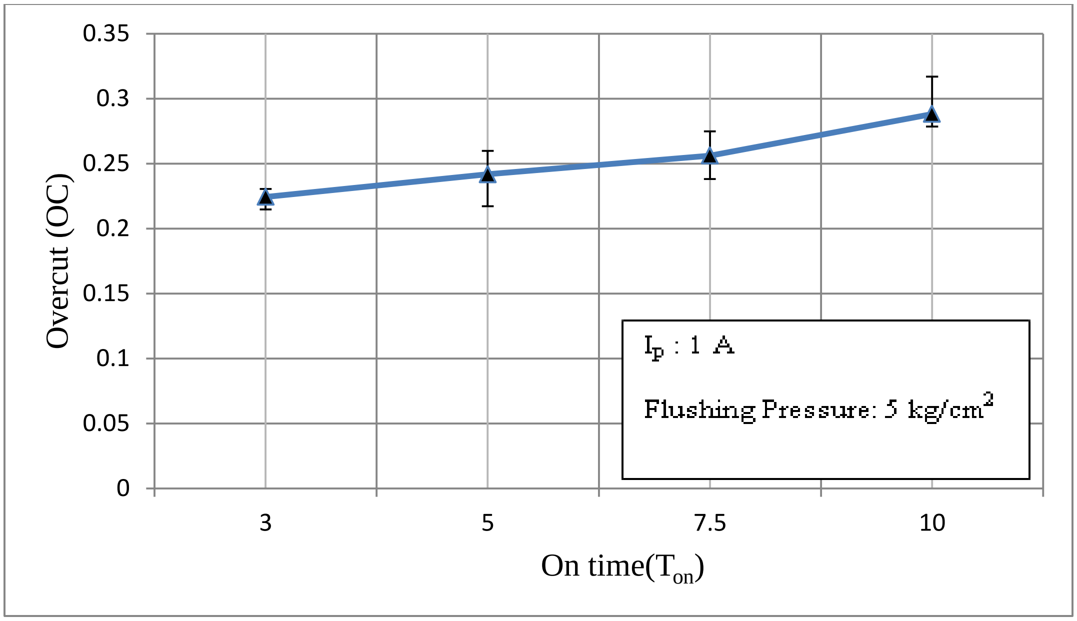
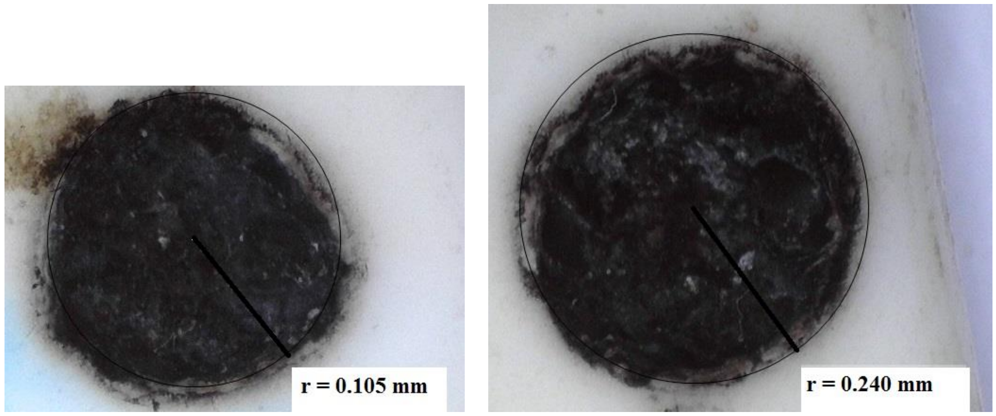


Fig.6.13. Variation of Overcut(OC) vs On time

(iii)Flushing pressure

Flushing pressure is one of the most significant parameters when machining materials using EDM. But the principle of machining non-conductive ceramics is different from that of conductive materials. In case of conductive materials overcut increases with increase in flushing pressure. This is because with the increment of flushing pressure more machined byproducts get removed from the machined surface which leads to increment of availability of fresh dielectric thus material removal rate increases. As overcut is directly proportional to MRR so, with the increment of flushing pressure overcut increases. But contrary to this in case of non-conductive ceramics flushing pressure have negative impact on overcut because increasing the flushing pressure continuously washes away the carbon layer being deposited on the workpeice during machining which leads to decrease in material removal rate as well as overcut as shown in Fig.6.15 The impact of flushing pressure on overcut has been shown in Fig.6.14 by measuring under LEICA microscope. It is clearly seen that overcut has decreased by increasing flushing pressure.



(a) (b)

Fig.6.14. Drilled blind hole on alumina

(a) At flushing pressure of 15kg/cm^2 (b) At flushing pressure of 5kg/cm^2

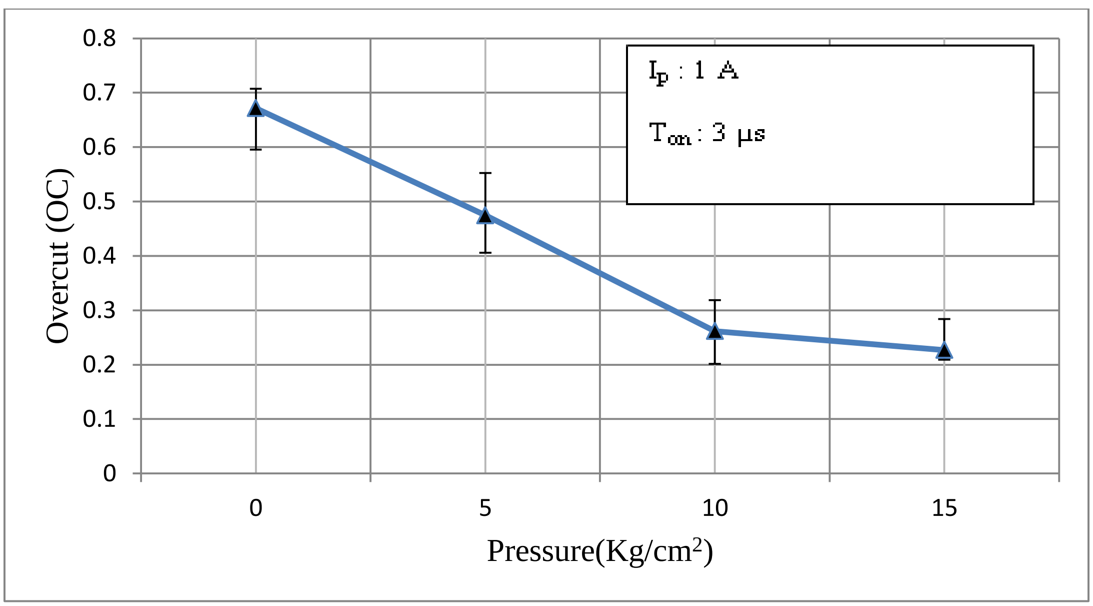


Fig.6.15. Variation of Overcut(OC) vs Flushing pressure

6.7. Results Obtained Based on the MCDM Techniques

In different MCDM methods, the final result obtained on the basis of some calculated mathematical value of each and every alternative. In this study, the whole interest is subjected to best three available alternatives from every MCDM analysis. Then the common best parametric combination has been obtained from every technique selected. That particular parameter setting has been further used to perform machining on Alumina (Al_2O_3) workpiece for validation of the result obtained.

Decision matrix has been formed on the basis of the parametric combinations based on which the experimentation has been done as depicted in Table 5.3. In this section most influencing parametric combination has to be searched out based on the steps followed in SAW, TOPSIS and MOORA method which have been mentioned in the earlier chapter.

1. TOPSIS method

In TOPSIS method normalised decision matrix has been obtained based on the Eq.16 as listed in below Table 6.1

Table 6.1. Normalised decision matrix obtained

Experiment no.	**MRR**	**TWR**	**Overcut(OC)**
1	0.4888	0.0361	0.9020
2	0.3638	0.0410	0.5485
3	0.2064	0.1060	0.4410
4	0.1768	1.0000	0.2875
5	0.9300	0.0325	0.3381
6	0.1261	0.0729	0.8676
7	0.1103	0.0760	1.0000
8	1.0000	0.1410	0.9394
9	0.5099	0.4478	0.8866
10	0.0591	0.9756	0.7881

In TOPSIS method, determination of positive ideal solution has been done by taking the maximum values of each column from the normalized decision matrix i.e 1, 1 and 1. Similarly, the negative ideal solution has been calculated by taking the minimum values of each column from the normalized decision matrix i.e.0.0591, 0.0325 and 0.2875.

Finally the ranking of the parametric combinations has been done based on the closeness index which is calculated with the help of separation measures i.e. Di^+ and Di^-. The values of Di^+ and Di^- have been calculated with the help of Eq.17 and Eq.18 as depicted in Table 6.2.

Table 6.2. Values of Separation measure

Experiment no	**(Di^+)**	**(Di^-)**	**R_i**	**Rank**
1	0.6323	0.4329	0.4064	
2	0.7137	0.2317	0.2451	
3	0.7619	0.1300	0.1457	
4	0.6288	0.5624	0.4722	
5	0.6776	0.5041	0.4266	
6	0.7397	0.3378	0.3135	
7	0.7407	0.4130	0.3580	
8	0.4969	0.6642	**0.5720**	**1st**
9	0.4313	0.4948	**0.5343**	**2nd**
10	0.5575	0.6161	**0.5250**	**3rd**

From the Table 6.2 it can be observed that the experiment number 8, 9 and 10 having separation measures of 0.5720, 0.5343 and 0.5250 respectively. So as per the result is concerned experimental parameter setting number 8 i.e. 1 A peak current, 5μs on time and 5 kg/cm2 flushing pressure is the best parametric combination as it comes by minimizing the non beneficial criteria and maximizing the beneficial criteria

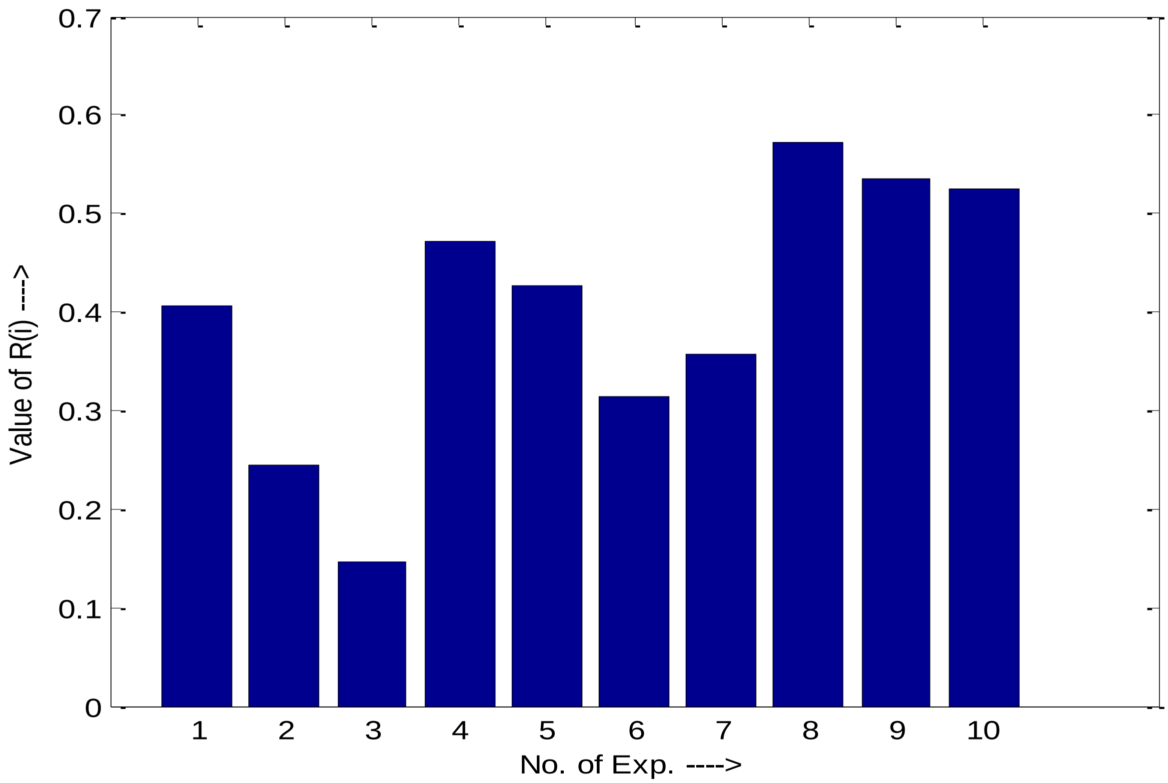


Fig.6.16. Graph showing the best parameteric condition using TOPSIS method

2. MOORA method

In MOORA method normalised decision matrix has been obtained on the basis of Eq.20 as listed in the following Table 6.3.

Table 6.3. Normalised decision matrix obtained

Experiment no	MRR	TWR	Overcut(OC)
1	0.3031	0.5217	0.1825
2	0.2255	0.4600	0.3002
3	0.1280	0.1779	0.3734
4	0.1096	0.0188	0.5727
5	0.5766	0.5796	0.4870
6	0.0782	0.2586	0.1898
7	0.0684	0.2480	0.1647
8	0.6200	0.1337	0.1753
9	0.3162	0.0421	0.1857
10	0.0366	0.0193	0.2089

The weighted normalised decision matrix in MOORA method is obtained by the Eq.21 as listed in the Table 6.4.

Table 6.4. Weighted normalised decision matrix obtained

Experiment no	MRR	TWR	Overcut
1	0.1012	0.1737	0.0608
2	0.0753	0.1532	0.1000
3	0.0427	0.0592	0.1243
4	0.0366	0.0063	0.1907
5	0.1926	0.1930	0.1622
6	0.0261	0.0861	0.0632
7	0.0228	0.0826	0.0548
8	0.2071	0.0445	0.0584
9	0.1056	0.0140	0.0618
10	0.0122	0.0064	0.0696

In MOORA method, the weighted multi objective optimization is done by calculating the the value of ‘a’ which is the sum of all weighted normalized values for all beneficial column i.e. 0.8224 and the value of ‘b’ i.e. the sum of all weighted normalized values for all non-beneficial column i.e. 0.2345, 0.2531, 0.1836, 0.1970, 0.3552, 0.1493, 0.1374, 0.1029, 0.0759 and 0.0760.

Finally, the ranking of the parametric combinations has been done based on the basis of final score value i.e. ‘a – b’ which is calculated with the help of the Eq.23 and the values of ‘a - b’ obtained are 0.5878, 0.5692, 0.6388, 0.6254, 0.4672, 0.6730, 0.6849, 0.7195, 0.7465 and 0.7463.

From Fig.6.17 below it can be observed that the experimental parameter setting number 9, 10 and 8 respectively having final score 0.7465, 0.7463 and 0.7195 respectively. So as per the result is concerned experimental parameter setting number 9 i.e. 1 A peak current, 7.5 µs on time and 5 kg/cm2 flushing pressure is the best parametric combination as it minimizes the non beneficial criteria and maximizes the beneficial criteria.

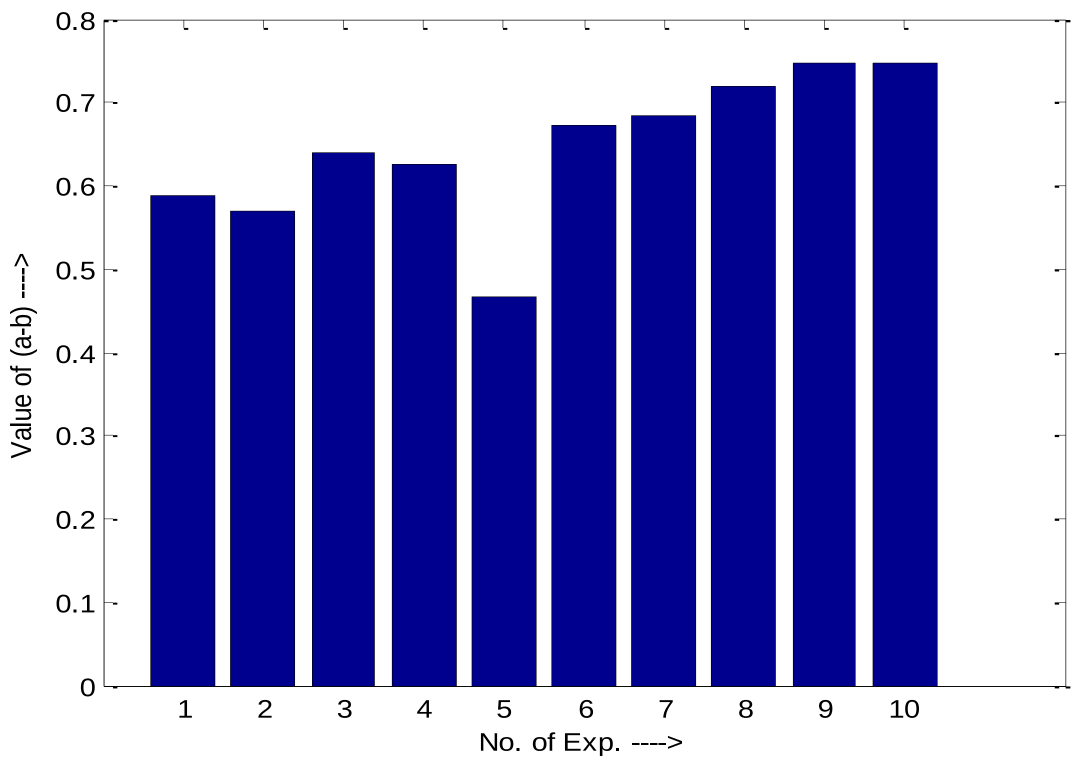


Fig.6.17. Graph showing the best parameteric condition using MOORA method

3. SAW method

In SAW method the normalised decision matrix has been obtained by Eq.10 as listed in the Table 6.5.

Table 6.5. Normalised decision matrix obtained

Experiment no.	**MRR**	**TWR**	**Overcut(OC)**
1	0.4888	0.0361	0.9020
2	0.3638	0.0410	0.5485
3	0.2064	0.1060	0.4410
4	0.1768	1.0000	0.2875
5	0.9300	0.0325	0.3381
6	0.1261	0.0729	0.8676
7	0.1103	0.0760	1.0000
8	1.0000	0.1410	0.9394
9	0.5099	0.4478	0.8866
10	0.0591	0.9756	0.7881

The weighted normalised decision matrix is calculated based on the Eq.11 as listed in Table 6.6.

Table 6.6. Weighted normalised decision matrix obtained

Experiment no	MRR	TWR	Overcut (OC)
1	0.1633	0.0120	0.3004
2	0.1215	0.0136	0.1826
3	0.0689	0.0353	0.1469
4	0.0591	0.3330	0.0957
5	0.3106	0.0108	0.1126
6	0.0421	0.0243	0.2889
7	0.0369	0.0253	0.3330
8	0.3340	0.0470	0.3128
9	0.1703	0.1491	0.2953
10	0.0197	0.3249	0.2624

In SAW method the value of composite score 's' is calculated by sum of all weighted normalized rows and is given by Eq.14 as listed in the Table 6.7.

Table 6.7. Composite score 's' by sum of all weighted normalized rows

Rank								**1st**	**2nd**	**3rd**
's'	0.4757	0.3178	0.2511	0.4878	0.434	0.3553	0.3952	0.6958	0.6147	0.6071

SAW method gives result on the basis of composite score 's'. From the above Table 6.7 , it can be observed that the experimental parameter setting number 8, 9 and 10 having composite score value 0.6958, 0.6147 and 0.6071 respectively. Therefore as per the result is concerned experimental parameter setting number 8 i.e. 1 A peak current, 5μs on time and 5 kg/cm2 flushing pressure is the best parametric combination as it minimizes the non beneficial criteria and maximizes the beneficial criteria as shown in the Fig.6.18.

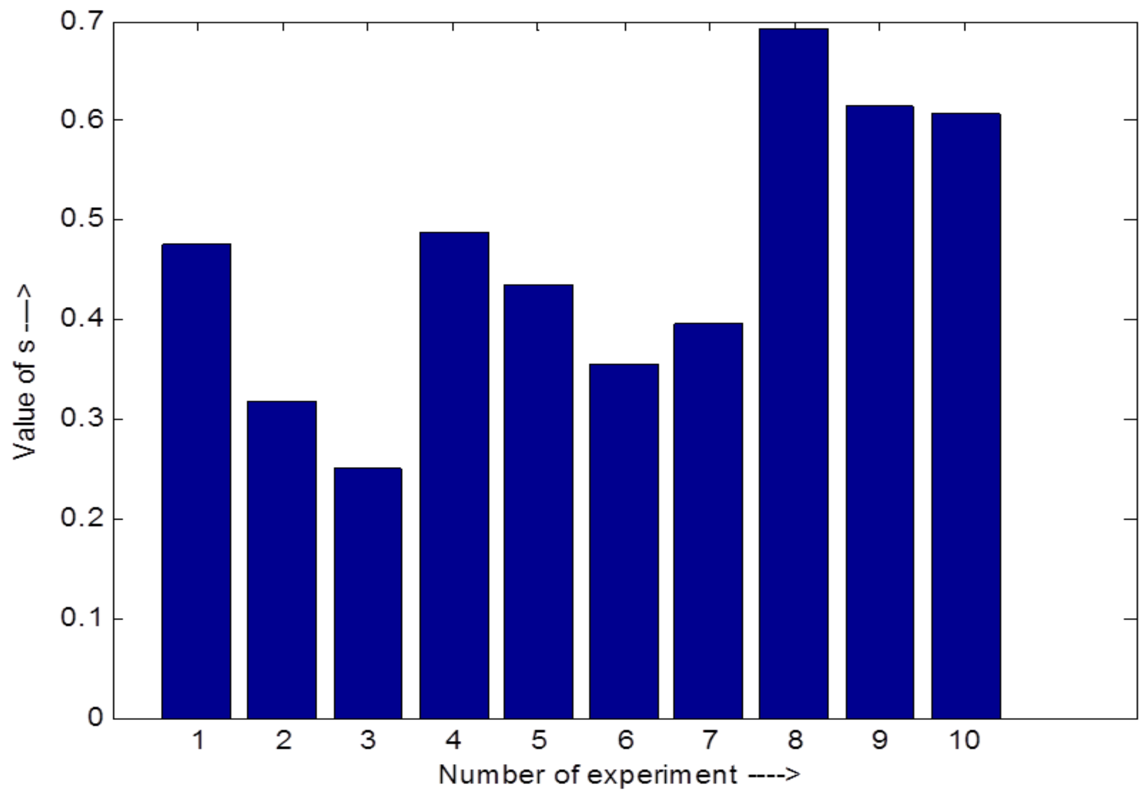
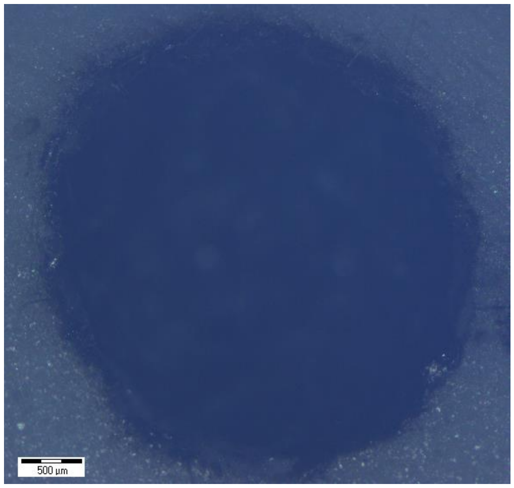
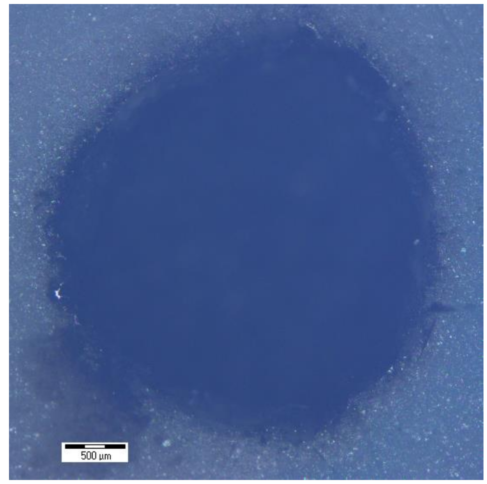


Fig.6.18. Graph showing the best parametric condition using SAW method

From the above three MCDM techniques it can be concluded that the TOPSIS and SAW method exhibits the same ranking i.e. row no. 8, 9 and 10, but MOORA gives the ranking 9, 10 and 8. But, it can also be seen from the Fig.6.17 that in MOORA method the value of (a-b) of experiment no 8, 9 and 10 are very close. Therefore, the best parametric combination considering all the three optimization techniques has been selected as experiment no. 8 i.e. peak current 1A, on time 5µs and flushing pressure 5kg/cm^2 which will give the best responses i.e. maximizing material removal rate (MRR) and minimizing tool wear rate (TWR) and overcut (OC).

Therefore, considering all the above results in this chapter it can be established that the best parametric combination obtained on the basis of the experiments performed by varying one process parameter at a time is the experiment no 1 i.e. peak current (I_p) 1 A, on time (T_{on}) 3µs and flushing pressure 5kg/cm^2, whereas, the best parametric combination obtained based on the optimization technique is the experiment no 8 i.e. peak current (I_p) 1 A, on time (T_{on}) 5µs and flushing pressure 5kg/cm^2. The machined alumina surfaces considering both the parametric conditions have been shown in the Fig.6.19 using LEICA microscope.





(a) (b)

Fig.6.19. Machined surfaces after removing the copper layer

(a) Machined hole at (1 A, 3 µs, 5kg/cm^2)

(b) Machined hole at (1 A, 5 µs, 5kg/cm^2)

From the above Fig.6.19 it has been very clearly observed that the quality and the accuracy of the drilled hole e.g. circularity, overcut etc. are better by using parametric combination obtained from the optimization technique as compared to the hole drilled using the experimental parametric combination. Therefore, it can be concluded that the parametric combination i.e. peak current (Ip) 1 A, on time (Ton) 5 µs and flushing pressure 5 kg/cm^2 is the best parametric combination in order to maximize MRR and minimize TWR and overcut (OC).

7. CONCLUSIONS AND FUTURE SCOPE OF RESEARCH WORK

EDM has great potential for cutting as well as drilling of electrically conducting and non-conducting materials e.g. ceramics. In this study, EDM has been performed on Al_2O_3 ceramic using ‘assisting electrode method’. Various process parameters have been varied and their corresponding effects on the responses such as material removal rate (MRR), tool wear rate (TWR) and overcut (OC) has been investigated. Furthermore, optimization of the process parameters based on three MCDM techniques i.e. SAW, TOPSIS, and MOORA method have been performed to find out the best parametric combination. Within the constraints of the experimental setup of EDM and based on the experimental investigations and analysis, following conclusions can be drawn:

(i) Using the modified EDM setup, machining can be performed successfully on the ceramic materials or any other low conductive materials.

(ii) The thickness of the coating layer on the ceramic surface plays a significant role on the machining of Al_2O_3 by assisting electrode method. It can be concluded that, as far as material of the assisting electrode is concerned, copper is best suited for EDM drilling of Al_2O_3.

(iii) Type of dielectric fluid has also major impact on EDM performances during machining of Al_2O_3. In comparison to deionizer water, EDM oil is best suited for machining of Al_2O_3 due to it’s ability to dissociate into hydro-carbons. This results in formation of pyrolytic carbon layer that is solely responsible for carrying out the further machining.

(iv) In EDM, the type of the tool electrode and it’s shape also play a vital role in the machining of Al_2O_3. In comparison with cylindrical tool, drill bit is appropriate for machining of Al_2O_3 because of better flushing as well as removal of the machined byproducts through the flute of the drill bit.

(v) After performing experimentation by varying one parameter at a time it has been concluded that peak current (Ip), on time (Ton) and flushing pressure are the most influencing parameters on the performance characteristics e.g. material removal rate (MRR), tool wear rate (TWR) and overcut (OC).

(vi) In this study, most optimal range of peak current, on time and flushing pressure are 1 to 4 A, 3 to10 µs and 0 to 15 kg/cm2 respectively during EDM drilling of Al_2O_3. From the experimentation, this has been observed that increasing peak current (Ip) decreases MRR and TWR but increases overcut (OC), similarly increasing on time (Ton) decreases MRR and TWR but increases overcut (OC). In case of flushing pressure all the three responses i.e. MRR, TWR and overcut (OC) decreases with increase in flushing pressure value.

(vii) From the experimentation by varying one process parameter at a time it has been observed that peak current (Ip) of 1 A, on time (Ton) of 3 µs and 5 kg/cm2 of flushing pressure is the best parametric combination.

(viii) After performing optimization using three MCDM techniques i.e. TOPSIS, SAW and MOORA it can be concluded that the parametric combination of experiment number 8 is the best combination for maximizing the material removal rate (MRR) and minimizing tool wear rate (TWR) and overcut (OC).

(ix) Finally, it has been observed that parametric combination opted from the MCDM techniques i.e. peak current (Ip) of 1 A, on time (Ton) of 5 µs and 5 kg/cm^2 of flushing pressure is best suited for EDM drilling of Al_2O_3 as far as accuracy and machined quality are concerned.

The present research work will help the manufacturing scientists as well as engineers for EDM machining of ceramic material Alumina (Al_2O_3) by assisting electrode method with copper as assisting electrode and tungsten carbide as tool. Performance characteristics such as MRR, TWR and overcut (OC) have been improved, however this area of research still required further study on performance characteristics like roundness, taperness, recast layer etc. At the end it is therefore felt that there is strong demand of research regarding EDM of other insulating ceramics as well concerning the understanding of the process.

The future scope of this research includes:

(i) Understanding the influence of other process parameters on other non-conducting ceramic and ceramic composites.

(ii) To understand the actual behavior of thermal ablation of the single insulating ceramics by multi-physics simulation techniques.

(iii) The effect of EDM process on the material properties of the machined non-conductive ceramics could also be extended in further research works. The use of non-destructive methods for measuring changes in material properties due to machining process is recommended.

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