CHAPTER-1

ELECTRICAL DISCHARGE MACHINING

1.1 Introduction

The history of EDM Machining techniques goes as far back as the 1770s when it was discovered by an English Scientist. The first EDM application was carried out by Mr. and Mrs. Lazarenko in the Technical Institute of Moscow during the Second World War. The first of the two important improvements also carried out by these Soviet scientists, who make it feasible to elevate this electrical technique to the category of manufacturing process, was the RC relaxation circuit, which provided the first consistent dependable control of pulse times. The second innovation consisted of adding a simple servo control circuit in order to find and holds a given gap automatically. In spite of these first trials and innovations, EDM technology got nearly unknown until the 1950s. At this time, this technique began to be interesting for the industrial marketing mainly in the USA. Some of the causes that eased a much more widespread use of the EDM process were the vacuum tubes, its combination with the basic RC relaxation circuit and finally, the development of the transistor. These solid state devices were able to provide highcurrents and much faster switch on and off than the previous vacuum tubes (I. J. Puertas *et al*).

Additional researchers entered the field and contributed many fundamental characteristicsof the machining method we know today. In 1952, the manufacturer Charmilles created the first machine using the spark machining process and was presented for the first time at the European Machine Tool Exhibition in 1955.

In 1969 Agie launched the world's first numerically controlled wire-cut EDMmachine. Seibu developed the first CNC wire EDM machine 1972 and the first system manufactured in Japan.Nowadays, EDM is widely used both in the European market and in the American market

Electric discharge machining (EDM), sometimes also referred to as spark machining, spark eroding, burning, die sinking or wire erosion, is a manufacturing process whereby a desired shape is obtained using electrical discharges (sparks).In the present day of globalization and technological advancement in industries like, an automobile, aeronautics, nuclear, mould, tools and die making industries, there is a heavy demand of the advanced materials with high strength, high hardness, temperature resistance and high strength to weight ratio etc. This necessity leads to evolution of advance materials like high strength alloys, ceramics, fiber-reinforced composites etc. In machining of these materials, conventional manufacturing processes are increasingly being replaced by more advanced techniques, which use different form of energy to remove the material because these advance materials are difficult to machine by the conventional machining processes, and it is difficult to attain good surface finish with close tolerance.

Electrical discharge machining is a machining method primarily used for hard metals or those that would be very difficult to machine with traditional techniques. EDM typically works with materials that are electrically conductive, although methods for machining insulating ceramics with EDM have also been proposed. EDM can cut intricate contours or cavities in pre-hardened steel without the need for heat treatment to soften and re-harden them. Also, applications of this process to shape polycrystalline diamond tools have been reported.

EDM is often included in the 'non-traditional' or 'non-conventional' group of machining methods together with processes such as electrochemical machining (ECM), water jet cutting (WJ, AWJ), laser cutting and opposite to the 'conventional' group (turning, milling, grinding, drilling and any other process whose material removal mechanism is essentially based on mechanical forces). To obtain a specific geometry, the EDM tool is guided along the desired path very close to the work; ideally it should not touch the workpiece, although in reality this may happen due to the performance of the specific motion control in use. In this way, a large number of current discharges (colloquially also called sparks) happen, each contributing to the removal of material from both tool and workpiece, where small craters are formed. The size of the craters is a function of the technological parameters set for the specific job at hand. They can be with typical dimensions ranging from the nano scale (in micro-EDM operations) to some hundreds of micrometers in roughing conditions.

The presence of these small craters on the tool results in the gradual erosion of the electrode. This erosion of the tool-electrode is also referred to as wear. Strategies are needed to counteract the detrimental effect of the wear on the geometry of the workpiece. One possibility is that of continuously replacing the tool-electrode during a machining operation. This is what happens if a continuously replaced wire is used as electrode. In this case, the correspondent EDM process is also called wire EDM. The tool-electrode can also be used in such a way that only a small portion of it is actually engaged in the machining process and this portion is changed on a regular basis.

1.2 Process Description

Spark Erosion Machining is a process based on the disintegration of the dielectric and current conduction between the Job and Workpiece by an electrical discharge occurring between them. This process is also called as Electro Discharge Machining/Electro Erosion Process/ Spark Machining. In this method the Job and the Work piece (which act as electrodes) are separated by a certain gap filled with a dielectric medium. A preset pulse is applied across the Job and Workpiece. Depending upon the micro irregularities of Tool and Workpiece surfaces, and presence of carbon and metal particles, the dielectric is broken down at several points producing ionized columns which allow a focused stream of electrons to flow and produces compression shock waves and there is an intense increase in the local temperature. Due to the combined effect of these two, particles of metal are thrown out, very much similar to the boiling out of water. As erosion progresses the gap changes and that gap is continuously maintained by the servomechanism.

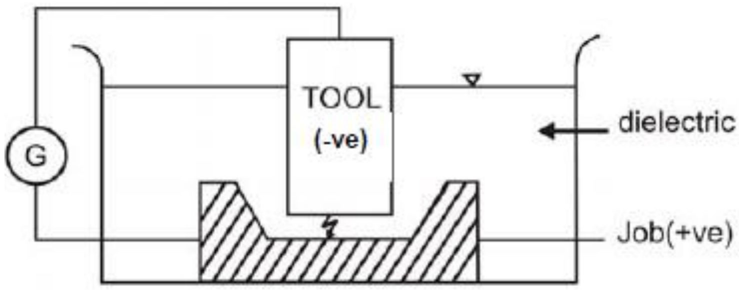

Fig 1 Schematic representation of the basic working principle of EDM process (Source: NPTEL)

1.3 Characteristics of EDM

(a) The process can be used to machine any work material if it is electrically conductive

(b) Material removal depends on mainly thermal properties of the work material rather than its strength, hardness etc.

(c) In EDM there is a physical tool and geometry of the tool is the positive impression of the holes or geometric feature machined

(d) The tool has to be electrically conductive as well. The tool wear once again depends on the thermal properties of the tool material

(e) Though the local temperature rise is rather high, still due to very small pulse on time, there is not enough time for the heat to diffuse and thus almost no increase in bulk temperature takes place. Thus the heat affected zone is limited to 2 - 4 μm of the spark

(f) However rapid heating and cooling and local high temperature leads to surface hardening which may be desirable in some applications

(g) Though there is a possibility of taper cut and overcut in EDM, they can be controlled and compensated.

These features allow this process to be used in producing fine slots or micro drills in thin delicate parts like electrical and electronic components. The Spark erosion process is effective in machining electrically conductive but extremely brittle material. In machining super hard material like cemented carbide, in removing broken drills, taps etc. Besides being used in the above application, this process can also replace the conventional extra laborious die cavity producing methods. Since the shape of cavity being eroded corresponds to the shape of tool, this process is very convenient and economical for various die-sinking applications.

As the Erosion is carried out in Dielectric medium the eroded particles get contaminated in dielectric as well on the machined surface. Due to the presence of these carbon particles the process gets affected. Hence it is necessary that such particles should be removed from dielectric continuously. This necessitates use of flushing and filtration system. For this, Spark Erosion Machines are provided with a combination of filter pumps system to control dielectric circulation. For flushing various methods like injection of dielectric in to sparking zone through electrode or workpiece or from sides in to the sparking zone is provided. It has been proved beyond doubt that flushing of dielectric improves the efficiency, accuracy and surface finish.

1.4 Dielectric System

In EDM, material removal mainly occurs due to thermal evaporation and melting. As thermal processing is required to be carried out in absence of oxygen so that the process can be controlled and oxidation avoided. Oxidation often leads to poor surface conductivity (electrical) of the workpiece hindering further machining. Hence, dielectric fluid should provide an oxygen free machining environment. Further it should have enough strong dielectric resistance so that it does not breakdown electrically too easily but at the same time ionize when electrons collide with its molecule. Moreover, during sparking it should be thermally resistant as well.

Generally kerosene and deionized water is used as dielectric fluid in EDM. Tap water cannot be used as it ionizes too early and thus breakdown due to presence of salts as impurities occur. Dielectric medium is generally flushed around the spark zone. It is also applied through the tool to achieve efficient removal of molten material. It is also a must that the carbon particles produced during erosion should be cleared from the sparking zone; hence various flushing techniques like injecting the filtered dielectric into the sparking zone. The system consists of pump, valves, filters and drain. A well-designed dielectric system to give trouble free circulation of the dielectric to the work tank has been provided.

A welded sheet metal tank is provided with the sheet metal cover placed near the machine tool. It consists of a 3 Phase, 415 Volts AC Monobloc Pump, Filter unit, Dielectric distributor consisting of a manifold with Flushing points at regular intervals suitable to flush out carbon particles throughout the job. It is connected to a 1 inch T with a Flexible pipe, which is connected to main inlet pipe. The other end of 1 inch "T" is connected to 1 inch Gate valve for flow of the dielectric into the work tank. The pump is fixed on mild steel plate and placed on the top of the dielectric system.

Filter Cartridges are mounted on a metal box. Metal pipe from the box is connected to the inlet of pump using flange with rubber gasket and fitted with nut and bolts. The kerosene is filled in to the tank. The amount of kerosene required depends upon the capacity of the filter tank. Flexible pipe coming from the 1 inch "T" from working tank has flange connected to it at one end. This flange is connected to the outlet of pump with nut and bolts along with rubber gaskets, which are provided. The Gate valve provides inlet of the dielectric (Kerosene) in to the work tank. Operating the Gate valve can control the flow of the dielectric. The excess flow can be by passed back to the filter tank by operating the other Gate valve provided near the pump. Operating the gate valves provided on the work tank can control the flushing pressure. Pressure gauge is provided to indicate the respective flushing pressure. A solenoid valve can also mount on the working tank (optional) and it serves for quick drain of the dielectric after the job is over. Pipeline for drain is provided from the working tank.

The filters cartridges should be replaced after every200-working hour of the *machine to* achieve the best results. Priming of the pump is to be done before the pump is put into operation.

1.5 Pressure Gauge

The flushing pressure can be read on separate gauge fitted on the left side of the working tank.

1.6 Flushing Techniques

The eroded products: i.e.

(a) Gases involved in the splitting of the dielectric fluid.

(b) Carbon particles (swarf) removed from the electrode & work piece are removed from the spark gap by appropriate devices.

The gases escape through the work-gap in the form of bubbles while the particles removed from the electrode and workpiece vary in size & shape, are washed away by flushing, hence there is always fresh between the spark gap. Care should be taken to avoid the flushing of kerosene opposite to each other. In case of jobs which have to be deeper than 10mm use the Auto flush. For deeper erosion process shorter should be the selection of CUT time. It is also advised to use flushing through the electrode/job wherever possible. Various types of flushing techniques have been shown in the figure. The basic types of flushing i.e. Pressure flushing and suction are differentiated in the figures, which are self-explanatory. If the work piece is having a through hole then the flushing pot is used as shown in the figure. If the electrode is of large size then we have to provide holes for flushing at more than one point e.g. for connecting rod electrode three holes for flushing are provided as shown in the figure. A electrode holding shank with central hole for flushing/suction is connected to flushing point/suction point using flexible pipe.

1.6.1 Flushing

Flushing is defined as correct circulation of dielectric fluid between work piece and tool. Suitable flushing is necessary for highest machining efficiency To start with dielectric should be fresh that is free from eroded particles and residue resulting from dielectric cracking and its insulation strength is high. With successive discharges dielectric gets contaminated, reducing its insulation strength and hence discharge can take place easily. If density of the particles becomes too high at certain points within the gap bridges are formed which lead to abnormal discharges and damage the tool as well as the work electrode .This buildup of the wear debris is eliminated by flushing. Flushing can be achieved by one of following methods:

1. Injection flushing
2. Suction flushing
3. Side flushing
4. Flushing by dielectric pumping

1.6.1.1 Suction Flushing

In this method dielectric is being suck either by tool electrode or work piece. Compared with injection flushing suction avoids tapering effects due to sparking via particles alongside of electrode. Suction flushing through tool rather than work piece is more efficient

1.6.1.2 Side Flushing

When flushing hole cannot be drilled either in the work piece or the tool this type of flushing is employed. For the entire work area to be evenly flushed

1.6.1.3 Flushing by Dielectric pumping

Flushing is obtained by using electrode pulsation movement. When the electrode is raised the gap increases resulting in clean dielectric being sucked into mix with contaminated fluid and as electrode is lowered the particles are flushed out.

1.6.1.4 Injection flushing

The dielectric fluid is injected into the working gap either through the work piece or tool. A hole is provided in the work piece or tool for this purpose.

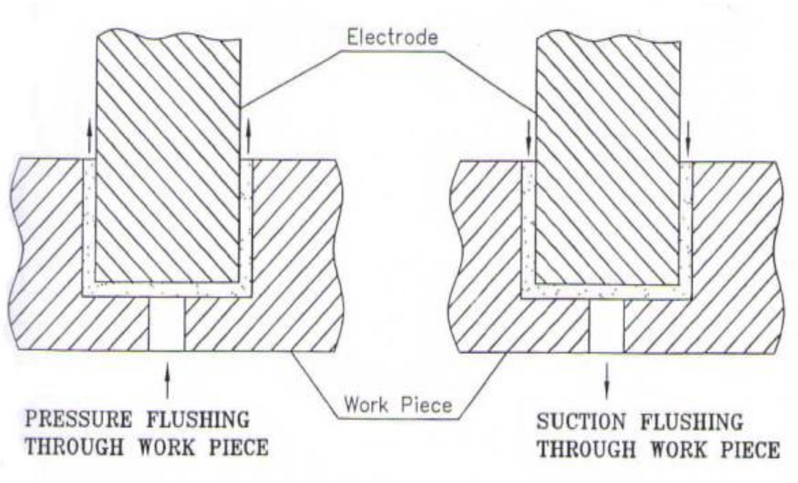

Fig 2 Injection Flushing

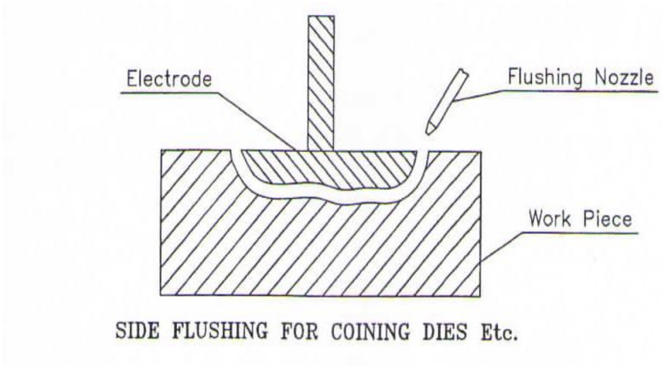

Fig 3 Side Flushing

CHAPTER-2

LITERATURE REVIEW

Electrical discharge machining (EDM) is one of the most extensively used non-conventional material removal processes. Its unique feature of using thermal energy to machine electrically conductive parts regardless of hardness has been its distinctive advantage in the manufacture of mould, die, automotive, aerospace and surgical components. In addition, EDM does not make direct contact between the electrode and the workpiece eliminating mechanical stresses, chatter and vibration problems during machining. A number of EDM variations based on this basic configuration have emerged in the industry to cope with the machining of exotic materials or super hard metal alloys used exclusively in the manufacture of aeronautical and aerospace parts (Ho and Newman, 2003).

Kruth Ir. J.P. *et al* (1995) in their research described the influence of workpiecematerial, electrode material and types of dielectric on the composition and the metallographic phases of thewhite layercausesat the surface of a workpiece.
Tests have beenperformed on the materials Impax, C35and Armco, machined in oil or water dielectric. In their research they have found that the use of an oil dielectric increases the carbon content in the white layer whereasa water dielectric on the other hand, causes a decarburization. The carbon in the white layer machined in anoil dielectric appears as iron carbides (Fe_3C) in columnar, dendritic structures.

Kunieda Masanori and Yoshida Masahiro (1997) have conducted their research on electrical discharge machining (EDM) in gas. They conducted their experiment withthe help of a high-pressure gas flow supplied through a thin-walled pipe electrode; the moltenworkpiece material can be removed and flushed out of the working gap without being reattached tothe electrode surfaces. The greatest advantage of this technique is that the tool electrode wears ratiois almost zero for any pulse duration. Hence a 3D shape can be machined very precisely using aspecial NCtool path which can supply a uniform high-velocity air flow over the working gap.Furthermore, the material removal rate is improved asthe concentration of oxygen in air is increased,due to oxidation of the electrode materials.

Wong Y.S. *et al* (1998) in their research have studied the effect of fine powder when added into the dielectric fluid as a suspension at the tool–workpiece or inter-electrode gap during machining.For thisstudy, the dielectric flushing system of a conventional die-sinking EDM machine was specially modified to inject anddistributethe powder into the dielectric fluid, especially at the gap between the tool and the workpiece. They studied the effect of different types of powder suspensions on various types of steel with at a peak current of around 1 A and particular combinations ofpowder-mixed dielectric and workpiece have been found to produce mirror-finish or glossy machined surfaces.

In their research they found that the powder has the effect of lowering the breakdown voltage so that discharges can occur at a wider inter-electrode gap, the wider gap facilitating flushing and reducing servo hunting so that machining is more stable. Al powder has been reported to give mirrorfinish workpiece in PMD-EDM for SKH-51 workpiece, whereas Al-impregnated dielectric does not seem to result in mirror-finish surfaces for PMD-EDMed SKH-54. The semi-conductive Si and C powders seem to be effective in bringing about very fine finish conditions. It appears that it is important to have the correct combination of powder and workpiece materials. An understanding of the fundamental mechanisms affecting such combinations will promote the applications of PMD-EDM to feasibly produce superior surface finish and properties of EDMed components

Chen S.L. *et al* (1999) in their paper studied the machining characteristics of Ti–6A1–4V with kerosene and distilled water as the dielectrics. They found that the material removal rate is greater and the relative electrode wear ratio is lower, when machining in distilled waterrather than in kerosene. By using X-ray diffraction, it is confirmed that carbide (TiC) and oxide (TiO) are formed on theworkpiece surface when using kerosene and distilled water, respectively. The lower removal rate when machining Ti–6A1–4Valloy in kerosene was due to the formation of TiC, which has a higher melting temperature and therefore requiresa larger discharge energy, and carbon deposition on the electrode, causing further retardation of the discharge process. Whereas a largeramount of debris and micro cracks are found when using distilled water as the dielectric.

Chow Han-Ming *et al* (2000) have presented a revised EDM process by quantitatively and qualitatively measuring the process using different dielectric fluids. They used a thin copper diskette electrode, titanium alloy as workpiece material and machined using micro-slit EDM with various dielectric fluids. The dielectric fluids used were kerosene, kerosene with aluminum powder, and kerosene with SiC powder. In their research they found that the Kerosene with either Al or SiC powder added in EDM can increase the material removal depth and thesurface roughness. However, without any powder added to kerosene, the electrode wear rate and the material removal depth are at the lowest minimum levels.

Kerosene with either Al or SiC powder added in EDM can extend the gap between the electrode and the workpiece. The added powder disperses the discharging energy to obtain superior surface roughness. Al powder with kerosene appears to be the best amongst the three different dielectric fluids.

Pecas P. and Henriques E. (2003) have conducted their research using silicon powderaiming to study the performance improvement of conventional EDM when used with a powder-mixed dielectric. They found the positive influence of the silicon powder in the reduction of the operating time, required to achieve a specific surface quality, and in the decrease of the surface roughness, allowing the generation of mirror-like surfaces. The use of 2 g/l silicon concentration suspended on the dielectric under conventional EDM conditions enhances the polishing process performance, smooth and high reflective craters were achieved. The average surface roughness (*R*a) depends on the area and varies between 0.09 µm for 1 cm^2 and 0.57 µm for 64 cm^2 electrode area. The presence of silicon in the dielectric almost eliminates the undesirable discharge conditions. Without silicon, the abnormal discharges remain present despite the longer processing time and limit the achievable final roughness.

Wang Kesheng *et al* (2003) in their research discussed the development and application of a hybrid artificial neural network and genetic algorism methodology to modeling and optimization of electro-discharge machining with graphite electrode and nickel based workpiece. The developed methodology with the model is highly beneficial to manufacturing industries, such as aerospace, automobile and tool making industries.

This hybrid approach is aimed to find an integrated solutionto the existing problem of modeling and optimization of manufacturing processes for which formulating anoptimization model is not straightforward, such as in the case of EDM.

Puertas I. and Luis C.J. (2003) in their research a modeling of the R_a and R_q parameters in function of I, ti and t_o factors has been carried out. In their research they found that the factor having the most important influence on the surface roughness is the factor of intensity.Furthermore, it has been observed that there is a strong interaction between I and the t_i. The fact of having to employ high I values to obtain a better surface roughness in this experiment may be due to a better arc stability causing a more uniform production of sparks and a narrow variation interval of the Ra and Rq roughness parameters. Moreover, it may be pointed out that depending on the extreme of I interval in which they have worked i.e. 0.5 or 6 A, there is a great deal of difference in the process duration (a difference of hours).

Gao Chang Shui and Liu Zhengxun (2003) have conducted their research on combined method of ultrasonic and electrical-discharge machining. The most noteworthy feature of the method is that the ultrasonic transducer does not vibrate the tool, as in traditional ultrasonic machining, but vibrates the workpiece. The findings of the experiment showed that the workpiece vibration induced by the ultrasonic action has a significant effect on the performance of the micro-EDM process. It was also found that the efficiency of the ultrasonically aided micro-EDM is eight times greater than that of micro-EDM when the workpiece thickness is 0.5 mm, the material is stainless steel, and the tool diameter is 43 µm. When material is tungsten, the results also show that the aspect ratio of the hole is noticeably increased.

Curodeau A *et al* (2004) in their research presents a variant of the standard die sinking EDM process, where a thermoplastic composite electrode, instead of solid graphite, is used to perform fine EDM finishing using air as dielectric mediumto perform automated polishing of tool steel cavity. It has been showed that composite thermoplastic electrodes have higher volume resistivity and lower wear resistance, due to their lower density as compared to solid graphite. An investigation of the properties of air has showed that it could be used to provide excellent surface finish since good control of the plasma discharge radius can be achieved by modulating the impulse current level. Finally, a proof of concept has demonstrated that the HEDP process can be used to reduce a 44μm *R*a surface finish down to a 36 μm *R*a with three electrodes forming iterations using constant EDM settings.

Klocke F. *et al* (2004) in their research paper studied the influence of powder suspended dielectrics on the recast layer has been considered. Therefore,a quantitative and qualitative measurement of the EDM process using an additional HSFC visualization system wasdeployed. The physical properties of the powder additives play an important role in changing the recast layer composition and morphology. From the findings of the research it has been concluded that Al powder leads to thinnest rimzone and the highest MMR. Based on the HSFC pictures the plasma channelis expanding in contrast to the standard dielectric. So the discharge energy is distributed on a bigger workpiecesurface and Si powder produces a grey zone beneath the actual “white zone”. That phenomenon can be explained by means ofthe Si-high heat of fusion property.

Singh Shankar *et al* (2004) have conducted the research to study the effects of machining parameters such as pulsed current on material removal rate, diameteral overcut, electrode wear, and surface roughness in electric discharge machining of En-31 tool steel (IS designation: T105 Cr 1 Mn 60) hardened and tempered to 55 HRc. After analyzing the results of the experiments on En-31 tool steel with different electrode materials, it was found that for the En-31 work material, copper and aluminium electrodes offer higher MRR.Diameteral overcut produced on En-31 is comparatively low when using copper and aluminium electrodes, whichmay be preferred for En-31 when low diameteral overcut (higher dimensional accuracy) is the requirement.Copper and copper–tungsten electrodes offer comparatively low electrode wear for the tested work material.Aluminium electrode also shows good results while brass wears the most, of all the tested electrodes.Of the four tested electrode materials, Cu and Al electrodes produce comparatively high surface roughnessfor the tested work material at high values of currents. Copper–tungsten electrode offers comparatively low valuesof surface roughness at high discharge currents giving good surface finish for tested work material.Copper is comparatively a better electrode materials as it gives better surface finish, low diameteral overcut,high MRR and less electrode wear for En-31 work material, and aluminium is next to copper in performance,and may be preferred where surface finish is not the requirement.

Zhan Bo Yu *et al* (2004) in their research have studied the machining characteristics between dry EDM milling, oil EDM milling and oil die sinking EDM and found that dry EDM milling is most advantageous to three-dimensional milling of cemented carbide considering the total machining time and cost.The results of experiments on the machining of cemented carbide using dry EDM and traditional oil EDM have shown that dry EDM milling shows higher machining speed and lower electrode wear ratio than oil EDM milling.Dry EDM milling can be used for the three-dimensional machining of cemented carbide.In comparing dry EDM with oil die sinking EDM for machining the same shape using cemented carbide, oildie sinking EDM shows shorter machining time.

Luis C.J. *et al* (2005) in their research have studied the material removal rate (MRR) and electrode wear (EW) in the die-sinking electrical discharge machining (EDM) of siliconised or reaction-bonded silicon carbide. This study was made only for the finish stages and has been carried out on the influence of five design factors: intensity supplied by the generator of the EDM machine (I), pulse time (ti), duty cycle (η), open-circuit voltage (U) and dielectric flushing pressure (P), over the two previously mentioned response variables.In the case of MRR, the only influential design factors, for a confidence level of 95%, were: intensity and voltage.

Kansal H.K. *et al* (2005) in their research studied to optimize the process parameters of powder mixed electrical discharge machining (PMEDM). Response surface methodology has been used to plan and analyze the experiments. The process variables chosen were pulse on time, duty cycle, peak current and concentration of the silicon powder added into the dielectric fluid of EDM to study the process

performance in terms of material removal rate and surface roughness. The silicon powder suspended in the dielectric fluid of EDM affects both MRR and SR. The slope of the curve indicates that the MRR increases with the increase in the concentration of the silicon powder. Therefore, more improvement in MRR is expected at still higher concentration level of silicon powder.
The analysis of variance revealed that the factor *C* (peak current) and factor *D* (concentration) are the most influential parameters on MRR and SR. The combination of high peak current and high concentration yields more MRR and smaller SR. The confirmation tests showed that the error between experimental and predicted values ofMRRand SR are within ±8% and −7.85% to 3.15%, respectively.

Yan Biing Hwa *et al* (2005) have conducted their research on pure titanium metals using urea into distilled water. In their experiments, machining parameters such as the dielectric type, peak current and pulse duration were changed to explore their effects on machining performance, including the material removal rate, electrode wear rate and surface roughness. They have also studied the elemental distribution of nitrogen on the machined surface by EPMA to assess the effects on surface modification. In their experiment they found that adding urea into the dielectric, MRR and EWR increased with an increase in peak current. When the urea was added to the dielectric, the surface roughness deteriorated with an increase in peak current. TiN was synthesized on the machined surface by chemical reactions that involved elements obtained from the workpiece and the urea solution dielectric during EDM.

Pradhan Mohan Kumar and Biswas Chandan Kumar (2008) conducted their experiments on AISI D2 tool steel with copper electrode with three process variables as discharge current, pulse duration, and pulse off time. They developed MRR models for three different parameters namely pulse current, discharge time, and pause time for EDM process using response surface method. The second-order response models have been validated with analysis of variance. They found that all the three machining parameters and some of their interactions have significant effect on MRR. It was found that discharge current, pulse duration, and pulse off time significant effect on the MRR. Model sufficiency was very satisfactory as the coefficient of determination was 0.962.

Vipin *et al* (2010) have developed computational modeling to predict the metal removal rate. The material for the work and the electrode has been taken as EN-31 and copper electrode respectively. The models were developed in terms of electrode diameter, current and pulse rate obtained experimentally. The Experimental data has been used to develop the models with the aid of regression analysis. The parametric investigations have also been explored by central composite design. They found that the material removal rate equation shows that the pulse rate is the main influencing factor, followed by current and electrode diameter in the operation model.Dual-response contours provide useful information about the maximum attainable material removal rate as a function of all three independent variables.For a particular MRR, Electrode diameter decreaseswith the increase in the current supplied.For a particular Electrode diameter, MRR increases withthe increase in the current supplied

Choudhary Rajesh *et al* (2010) have conducted their experiments on the machining of EN-31 die steel to study the heat affected zones (HAZ) with kerosene oilas dielectric fluid and different electrode materials (copper, brass and graphite) with electrical discharge machining (EDM) process. From the experiments they have found that copper electrodes offer highMRR as compared to the machining performedby graphite and brass electrodes.Among the three tested electrode materials, brass electrodes produce comparatively highsurface finish for the tested work material at high values of discharge current, whilegraphite shows the poor surface finish.It has been observed that with the increase of the discharge energy, the amount of debrisparticles in the gap becomes too large which form electrically conductive path betweenthe tool electrode and the workpiece, causing unwanted discharges that damages both the electrode surfaces.All three workpiece machined by different electrodes materials shows different patternof heat affected zones.In case of graphite electrode heat affected zone is much deeper as compared to copperand brass electrode.

Medfai A. *et al* (2011) have developed a mathematical model for the effect of cutting parameters on the machining by electro discharge machining used widely in industrial applications. From their experiments they found that Volume of removal material, MRR flow, and the surface quality Ra , increase for a varying current of discharge from 8 to 16 Amps. The use of an electrolytic copper electrode (e = 1.72 μ cm) generates a higher material flow than that of machining with the graphite electrode with the same conditions of machining.Average roughness is lower in the case of the use the electrolytic copper electrode.

Baraskar S. *et al* (2011) have developed mathematical models for SR, MRR and TWR for most significant process parameters namely discharge current, pulse-on time and pulse-off time using responsesurface methodology in EDM process of EN-8 steel with copperelectrode.Based on the experimental results, they found that experimental values of SR, MRR and TWR can satisfactorily be predicted from experimental diagrams of response surfaces and contour graphs. Results showed that central composite design is a powerful tool for providing experimental diagrams and statistical-mathematical models, to perform the experiments efficiently and economically. Most influencing factor in case of surface roughness is the discharge current. For all values of discharge current, surface roughness increases with the increase of pulse-on time settings and when pulse-on time is further increased the surface roughness decreases. Pulse-off time has shown negligible influence on SR. The MRR increases linearly with the increase of all values of discharge current. While the MRR value first increases with the increase of pulse-on time up to a specified value of 530μs, however MRR decreases when the pulse-on time is further increased. Absolute TWR increases nonlinearly as the current density increases up to 15A after this it starts decreasing for the range of investigation carried out.

CHAPTER-3

EXPERIMENTAL SETUP

3.1 Introduction

The experiments for the present case have been conducted on Spark erosion machine (SPARKMAN SN-35, Sparkonix) as shown in Fig.4. The machine has maximum current capacity of 35 amps. The experiment has been conducted in straight polarity i.e. the tool is connected to the negative terminal whereas workpiece is connected to the positive terminal. In the present study the optimal condition of MRR has been evaluated with the correlation of machining parameters like discharge current, pulse on time, pulse off time. The machining conditions used during experimentation have been shown in table1. Work piece material was cut into rectangular cross section and top and bottom faces of the work piece were ground to make flat and good surface finish prior to experimentation. A photograph of the EDMed work piece is shown in fig 10.

Fig 4 Electrical discharge machine (model sn-35)

3.2 Control Panel Description

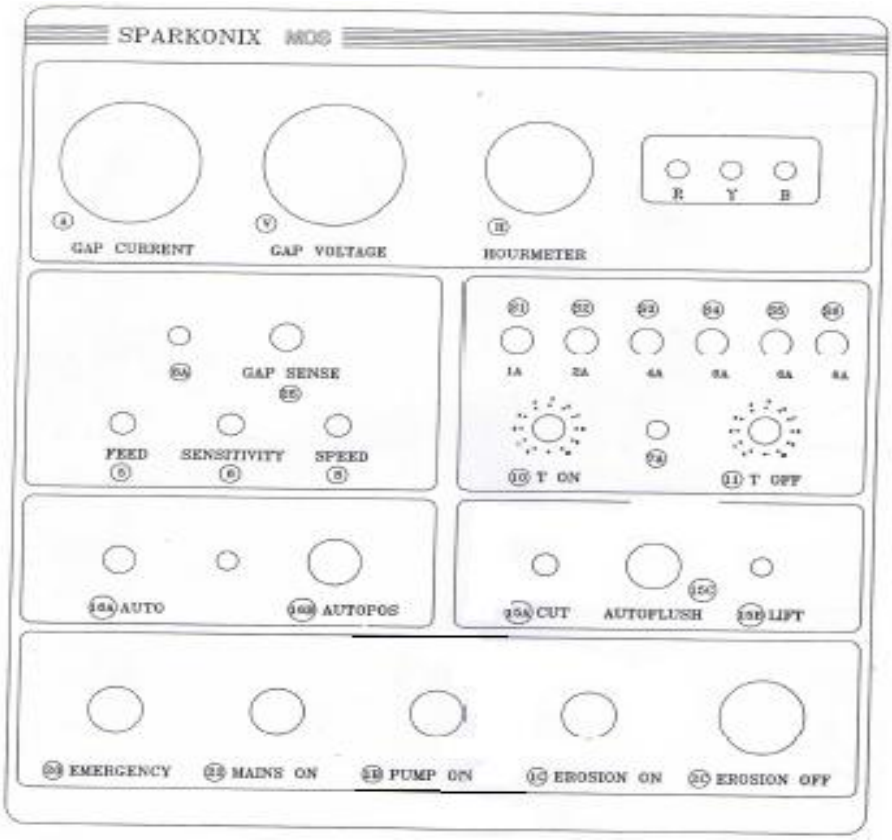

Fig 5 Control Panel

The control Panel of machine is as shown overleaf. The controls are numbered to make it simple.

3.2.1.Mains Switch (No.22)

The mains supply of 415 V for machine in switched ON by this push button switch provided with indicator.

3.2.2Pump on Switch with Indicator (No. 1 B)

The dielectric pump is switched ON by switch 1 B. The AUTO/MANUAL switch (No.16A should be in auto mode for making the pump/pumps on.

3.2.3. Erosion on Switch with Indicator (No.1C)

Erosion is switched 'ON' by switch No. 1 C. Ensure that AUTO/Manual switch (N0.I6A) is in AUTO mode.

3.2.4. Erosion Off Switch (No. 2C)

The Dielectric pump as well as Erosion is switched OFF by switch No. 2C

3.2.5.Emergency Switch (No. 20)

3y pushing this switch the mains supply of the machine will be cut off.

3.2.6.Speed Control (No. 8)

This knob is provided to control the speed of the quill motor during the manual movement, Autopos and during erosion.

3.2.7.Pulse Generator Indicating Lamp (No. 7 **A)**

This lamp is provided to indicate the working on pulse generator.

3.2.8. Power Switch (No. S1 TO S10)

Operating the different switches selecting different currents provided on the front panel does current selection for erosion.The number of switches depends upon generator rating i.e. SN 15, SN25 etc.

3.2.9. T_{on}Switch (No. 10)

With this switch the ON TIME of the pulse can be controlled in 11 steps i.e. from 0 to 10.

3.2.10. T_{off}Switch (No. 11)

With this switch the off time of the pulse can be controlled in 11 i.e. steps from 0 to 10

3.2.11.Auto Flush Switch (No.15C)

This switch is used to switch on the Auto-flush timer. When kept on during erosion process it lifts and resets the electrode according to the setting of the knobs (15A & 15B) so that the Carbon depositions in between the job and electrode are flushed out.

3.2.12. Voltmeter (No. V)

Actual sparking voltage is indicated on this meter. It is calibrated from 0 to 200V.

3.2.13. Ammeter (No. A)

Actual sparking current is indicated on this meter. It is calibrated as per controller rating.

3.2.14. Feed Balance Knob (No. 5)

This knob is provided to give proper feed to the motor. When the knob is operated together with sensitivity knob the sparking voltage can be set between 45 to 50 Volts and steady sparking can be achieved.

3.2.15. Sensitivity Balance Knob (No. 6)

This is the master knob for controlling the forward and reverse movement of the motor when sparking as well as Autopos. Avoid using the knob in Zero or low position, as there is chance of bending of electrode in AUTOPOS mode. In sparking mode the knob is set along with Feed knob for sparking between 45-50V on the voltmeter. This knob when operated in clockwise mode the motor goes reverse (UP) indicated by red glow on indicator No. 4. When it is taken anticlockwise after certain position the indicator glows green and motor starts moving down and sparking will start.

3.2.16.Indicator Lamp for Steady Erosion (No. 6A)

This lamp indicates the forward (Green) and reverse (Red) movement of the Z axis motor. During sparking it shows the combination of both for steady erosion.

3.2.17. **Gap Sense (No. 25)**

This knob is provided to detect ARCING CONDITION occurring between Job and electrode. Depending on the possibility of arcing in the job, the sensitivity should be set by this knob. In arcing condition the motor will reverse along with the whistling of buzzer. When this occurs the voltmeter will also shows Z E RO reading. If this condition repeats continuously the operator must lift the electrode from the job and clean the arc head (Carbon Ball) inside the job and also from the electrode.

3.2.18.Hour Meter (No. H)

The HOUR METER indicates the reading in hours to calculate the time required to do a particular job.

3.3 Pendent Panel Description

3.3.1. Manual Control for Quill Movement

Two switches are provided for upward and downward movement of the servo head on the Pendent panel. During this operation the Auto/Manual SWITCH (No. 16A) should be in MANUAL mode. In this mode the motor does not stop even if the electrode touches the job hence care should be taken that the electrode is far away from the workpiece otherwise it will bend and get damaged if it hits the job.

3.3.2. **X-Y Movement for Servo Head**

This function is provided exclusively for controlling the X**-Y** Movement of the Servo Head. There are four push buttons switches with direction.

3.3.3. **Auto/Manual (No. 16A)**

When this switch put in AUTO mode we can actuate the AUTOPOS switch and when in this mode the Autopos buzzer sounds when Electrode touches the Roll/Ring. We can move the Z-axis manually up/down by using the respective switches provided when this switch is in MANUAL mode. This switch should be at AUTO mode for making the pumps on as well as EROSION on.

3.3.4. Autopos (No. 16B)

When this push button switch is actuated LED will glow and the Z-axis motor will rotate in forward movement, at this time the AUTO/MANUAL switch should be in AUTO mode. When the electrode touches the job, AUTOPOS buzzer sounds. Care should be taken that sensitivity knob is not too low or zero otherwise there is a chance of electrode bending. This buzzer facility is provided for zero setting on dial and depth setting on micrometer.

3.4 Controller Description

The controller supplies electrical energy to the Spark gap in the form of square wave pulses. Precision timing and control of the pulses in the spark controller results in stable sparking.

Features:

- Based on MOSFET, which ensures reliable consistent sparking in low and high frequency operations.
- Auto lift/cut of the electrode at adjustable timing.
- DC stepper drives on quill movement for rapid movement in manual mode andcontrolled speed in sparking mode.
- Gap sense (Anti-Arc) facility to prevent arcing and possibility of damages to electrode and job.
- Different selectable settings.
- Autopos and Zero setting facility with Audio/visual signal device for positioning of electrode and precise depth setting.
- EPROM input by crystal controlled oscillator.

All components in the controller are assembled in standard cabinet. Opening respective panels can easily access the sub-assemblies in the controller. All controls are easily assessable to avoid the overheating by an efficient cooling system with circular fan. The controller works on 415 V AC, 3 Phase + /-10%, 50Hz power supply. Sparkman MOS consists of EPROM based pulse generator for roughing as well as fine finishing operations.

EPROM based pulse cum fine generator

The discharge current in spark gap is selected by means of current selector switches. The working current can be selected depending upon sparking area. Different values of current can be switched ON individually. The generator consists of T_{on} and T_{off} switches provided on the control panel. According to the adjustment of T_{on} time and T_{off} time the machining mean current can be below maximum peak current. The values are at a working voltage of approximately 45 to 50 volts. The ON time duration for which the pulse is switched ON and OFF time is the duration for which the pulse is switched off. This is fixed by means of an electronic time base and chosen by setting 11-position pulse time selector to maximize the efficiency in roughing and finishing operations.

The Pulse ON time determines the energy of each discharge for given power. The longer the duration of the pulse, the greater the energy per discharge, the craters produced being deeper and the surface finish rougher. The duration of the pulses for a given power (Current) determines the surface finish and the rater of wear and Material Removal Rate (M.R.R.).

The Pulse off time determines the spacing of the pulses i.e. the frequency of the succession of the pulses. It is thus possible to modify the speed of sparking for a given pulse ON time. Modification of Pulse OFF time has no effect on the surface finish. This selector is adjusted so that both speed and stability of sparking are obtained. The T_{on} time should always be more than T_{off} time by one or two divisions. Finishing can be achieved at very low current with very low T_{on} and T_{off} timings.

Optional:

The operator has to set important parameters on the from panel or control panel which influences considerably the material removal rate (M.R.R.) electrode wear, surface finish and over cut. They are -

- Sparking on generator with variable pulse duration i.e. T_{on} and T_{off} timing.
- Sparking Current.
- Feed and Sensitivity control along with the speed control.
- Mode of flushing.

3.5 Setting of Workpiece for Spark Erosion

The procedure for setting the JOB in spark erosion is similar to other conventional machines except for certain precautions regarding limitations of the process.

Mounting of Workpiece

The Workpiece can be located at the desired place on the T slot table by opening the door of the tank, then clamp the workpiece which are provided or on magnetic block, magnetic vice etc. If any reference edge is to be checked then the gauge or marking block should be held in the electrode holder and checked with the help of X-Y coordinate movement. After clamping the job and setting it properly hold the electrode firmly in the V block. Use a rectangular or a square shank instead of a round one to check whether Electrode is perpendicular or not. By X-Y coordinate and Servo slide movements the Electrode should be located over the desired cavity. Then adjust the float switch so that the dielectric level is at least 5cm.above the topmost sparking point. Then close the door firmly with the clamps. The job is now set and we may proceed for operating the machine as per instructions given in the manual.

Electrode Clamping

- In order to make round or square cavity an Electrode of that shape should be clamped directly on the V-Block as shown in the adjoining figure.
- If there is a big electrode than one has to make use of other shanks. The shank is lightly screwed on to the Electrode first and is then clamped on the V Block. Shank with an internal hole is to be used for suction or injection flushing system.
- Special electrode holder and rotary mechanism for fine drilling of holes is provided and that it can be clamped on the V-block holder.
- For gang drilling the special jigs and fixtures are available.

Relocating of Electrode

In most of the operations relocating of the electrode is required and can be obtained by following ways:

- By using a relocating shank which ^has a right angle which fits in the V-block holder (as shown in the figure) so that after removing and clamping again it will retain the position.

- After removing the electrode mark its position by scriber on the job and relocate the shank in such a position that the marking on the job and electrode coincide.
- But the most practical method of relocating is by starting the controller on very low power of pulse generator, please see to it that dielectric is not present on the job as well as in the tank while observing sparking.
- Autopos function can also be used for relocating of electrode, e.g. entering of the job and electrode.

Alignment of Electrode

- Roughly it is checked by master try square.
- It is also checked by dial gauge as follows,

Its alignment is checked at two places which should be perpendicular to each other as shown in the figure. It should be within 0.02 mm for a length of 100mm. The dial gauge is held over by a magnetic block and the electrode is moved up and down manually by Quill motor.

Swiveling Mechanism

Electrode can be made perpendicular to the work piece surface by swiveling of electrode with the help of 4 bolts shown in the figure. The electrode can be swiveled maximum 7 degrees in the vertical plain. The dial gauge or metal try square can be used to check the perpendicularity.

3.6 Process Parameters

Discharge Voltage

The spark gap and breakdown strength of the dielectric in the EDM is depending upon the discharge voltage. Before current can flow, the open gap voltage increases until it creates 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.

Peak Current

This is the most important machining parameter in EDM. It is the amount of power used in discharge machining, measured in units of amperage. During each on-time

(T_{ON}) pulse, the current increases until it reaches a preset level, which is expressed as the peak current. Higher currents will improve MRR.

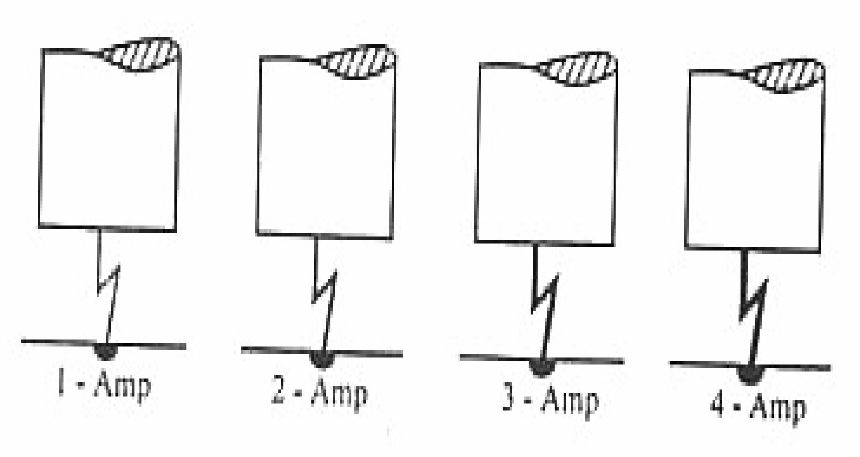

Fig 6 Shows effect of current on surface

Pulse On-time & Off-time

Each cycle has an on-time (T_{ON}) and off-time (T_{OFF}) 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 will be deeper and broader than a crater produced by a shorter on-time. Excessive on-times can be counterproductive when the optimum on-time for each electrode-work material combination is exceeded, material rate starts to decrease.

The cycle is completed when sufficient off-time is allowed before the start of the next cycle. Off time will affect the speed and stability of the cut. Shorter the off-time, the faster will be the machining operation. However, if the off-time is too short, the ejected work piece material will not be swept away by the flow of the dielectric and the fluid will not be deionized. This 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.

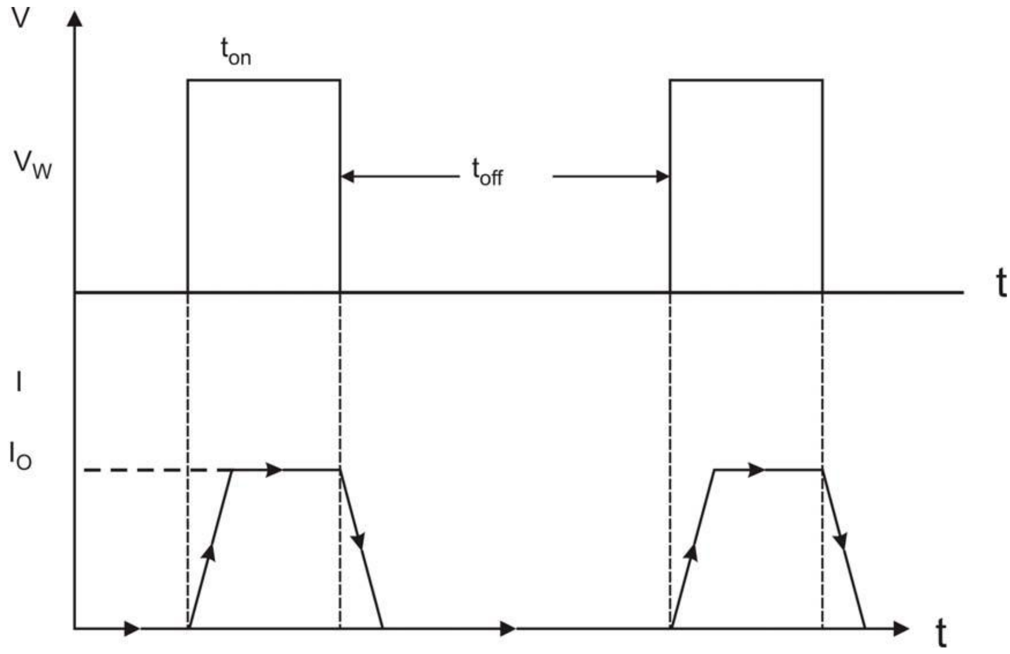

Fig 7 Concept of Pulse on Time and Pulse off Time(Source: NPTEL)

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. However while longer discharges, the early electron process predominance changes to positron process, resulting in high tool wear. In this experiment setup, positive polarity is selected.

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.

Frequency

This is a measure of the number of times the current is turned on and off. During roughing, the ‘on time’ is increased significantly for high removal rates and fewer cycles per second, hence a lower frequency setting as shown in Figure. Frequency is distinct from the duty cycle, as this is a measure of efficiency.

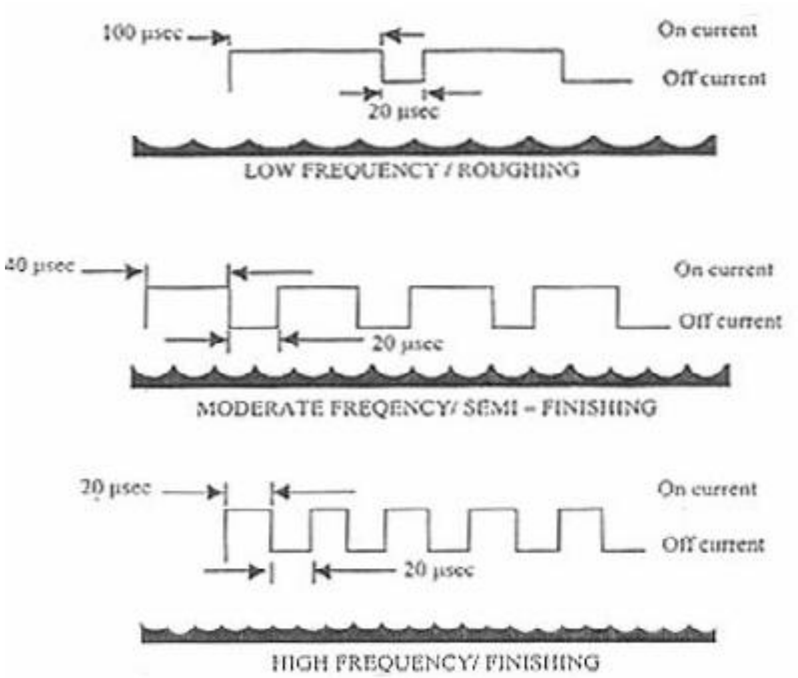

Fig 8 Frequency setting

Electrode Material

Electrode material should be such that it would not undergo much tool wear when it is impinged by positive ions. Thus the localized temperature rise has to be less by tailoring or properly choosing its properties or even when temperature increases, there would be less melting. Further, the tool should be easily workable as intricate shaped geometric features are machined in EDM. Thus the basic characteristics of electrode materials are:

• High electrical conductivity - electrons are cold emitted more easily and there is less bulk electrical heating

• High thermal conductivity - for the same heat load, the local temperature rise would be less due to faster heat conducted to the bulk of the tool and thus less tool wear

• Higher density - for the same heat load and same tool wear by weight there would be less volume removal or tool wear and thus less dimensional loss or inaccuracy

• High melting point - high melting point leads to fewer tools wear due to less tool material melting for the same heat load

• Easy manufacturability&Cost - cheap

The followings are the different electrode materials which are used commonly in the industry:

• Graphite

• Electrolytic oxygen free copper

• Tellurium copper - 99% Cu + 0.5% tellurium

• Brass

Surface Finish

The surface produced by the EDM process consists of a multitude of small craters randomly distributed all over the machined face. The quality of surface finish depends upon energy per spark. If energy content is higher deeper crater will result leading to poor surface. The surface roughness has been found to be inversely proportional to frequency of discharge.

CHAPTER 4

MATHEMATICAL MODELLING

Introduction to Regression Analysis

Regression analysis is the process of developing a statistical model, which is used to predict the value of a dependent variable by at least one independent variable. In simple linear regression analysis, there are two types of variables. The variable whose value is influenced or is to be predicted is called the dependent variable and the variable which influences the value or is used for prediction is called the independent variable. In regression analysis, the independent variable is also known as regressor or predictor or explanatory while the dependent variable is also known as regressed or explained variable.The term multiple *regression* literally means stepping back toward the average. It was use by British mathematician Sir Francis Galton .Regression analysis is a mathematical measure of the average relationship between two or more variables in terms of the original units of the data.

Determining the Equation of a Regression Line

Simple linear regression is based on the slope-intercept equation of a line. This equation is given as

$y = ax + b$

Where a is the slope of the line and b the y intercept of the line.

The straight line regression model with respect to population parameters β_0 and β_1 can be given as

$\mathbf{y}= \beta_0+ \beta_1 x$

Where $\beta_0 0$ is the population y intercept which represents the average value of the when $x = 0$ and β_1 the slope of the regression line which indicates expected change in the value of y for per unit change in the value of x.

A probabilistic model is given as

$\mathbf{y}= \beta_0+ \beta_1 x + \varepsilon$

In the deterministic model, all the points are assumed to be on the regression line and hence in all cases random error ε is equal to zero. Probabilistic model includes an error term which allows the value of y to vary for any given value of x.

Multiple Regression Analysisis use when more than two parameters are used. In my thesis there are 3 parameters so I will consider multiple regression analysis. In multiple regressions analysis linear equation is given by:

$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \dots\dots\dots + \beta_k x_k + \varepsilon$

Where $y_i$is the value of the dependent variable for ith value, $\beta_0$the y intercepts, $\beta_1, \beta_2, \beta_3 \dots \beta_k$ is the slope of y with independent variable $x_2, x_3, \dots\dots x_k$. Some terms which are considered in multiple regressions are discussed below:

Nonlinear Regression Model

Nonlinear regression plays an important role in understanding the complex inter-relationships among variables. A nonlinear model is one in which at least one of the parameters appears nonlinearly. Examples of a nonlinear model are:

$Y(t) = \exp(at+bt^2)$ ----------- (1)

$Y(t) = at + \exp(-bt)$

It is also called 'intrinsically linear' which can be transformed to a linear model by means of some transformation. For example the model given in above as equation (1) is intrinsically linear in view of the transformation X (t) = log Y (t)

Sampling Error

When estimating a population parameter from a sample it is important not only to derive a specific value but also estimate the effect of the sampling error on the estimate. To accomplish this it is necessary to consider the concept of a sampling distribution for a regression coefficient. This could be easily understood as the distribution of estimates of the regression coefficient that would be result if sample of given size were drawn repeatedly from the population and coefficient calculated from each sample. Because coefficient estimated from random samples will deviate from populations values by varying amounts, the estimates, the estimates of the coefficient from a series of random samples of population will not be identical but instead will distribute themselves around a mean. The estimated standard deviation of the sampling distribution of regression coefficients is known as a *standard error* and is denoted by 'ε'.

This is called ***coefficient of determination*** indicates explanatory power of any regression model. Its value lies between +1 and 0. It can also been shown that R –sq is the correlation between actual and predicted value. It will reach maximum value when dependent variable is perfectly predicted by regression equation.

Residual Analysis

The prediction errors from a regression model are also called residuals. Analysis of these residuals can help us to detect the violations of certain regression assumption. It helps us to identify OUTLIERS and to improve the model. In my thesis work i try to compare between linear equation and polynomial equation with the help of RESIDUAL ANALYSIS and R-sq value. Model which will have less outliers and higher R-sq will be final model for MRR and hardness. For this I will again take the help of MINITAB15

Determination of Coefficient of Multiple Regressions (R^2):

The coefficient of determination (r^2) is the proportion of variation in dependent variable y that is explained by the combination of independent variables.

$$r_y^2 = \frac{regression\, sum\, of\ squares}{total\, sum\, of\ squares} = \frac{SSR}{SST}$$

Adjusted R^2:

Adjusted *R2* is commonly used when a researcher wants to compare two or more regression models having the same dependent variable but different number of independent variables.

$$Adjusted\ R^2 = 1 - \frac{SSE / n-k-1}{SST / n-1}$$

Where n is number of observations and k is number of independent variables.

Standard Error of the estimate:

Standard error can be understood as the standard deviation **of** errors (residuals) around the regression line. In a multiple regression model, the standard error of the estimate can be computed as

$$\text{Standard error } = \sqrt{\frac{SSE}{n-k-1}}$$

Where *n* is the number of observations and *k* the number of independent (explanatory) variables.

Testing the statistical significance of the overall regression model:

Testing the statistical significance of the overall regression model can be performed by setting the following hypotheses:

H_0: $\beta_1 = \beta_2 = \beta_3 = \ldots = \beta_k = 0$

H_1: At least one regression coefficient is $\neq 0$

or

H_0: A linear relationship does not exist between the dependent and independent variables.

H_1: A linear relationship exists between dependent variable and at least one of the independent variables.

In case of a multiple regression model, the *F* test determines that at least one ofthe regression coefficients is different from zero.

For multiple regression *F* statistic can be defined as

$$\mathrm{F} = \frac{MSR}{MSE}$$

Where

$$MSR = \frac{SSR}{k}$$

$$MSE = \frac{SSE}{n-k-1}$$

Where *k* is the number of independent (explanatory) variables in the regression model

CHAPTER 5

EXPERIMENTAL ANALYSIS

Electrical Discharge Machining or Spark Erosion is one of the most modern methods used for manufacture of complex recessed parts viz. molds or dies. Sparks are generated between an electrode and the job, which is submerged in insulating medium dielectric. Dielectric oil should have proper di-electric value, and also not create a fire hazard. A scientific approach to plan the experiments is a necessity for efficient conduct of experiments. There are two aspects of an experimental problem: the design of the experiments and the statistical analysis of the data. These two points are closely related since the method of analysis depends directly on the design of experiments employed. The advantages of design of experiments are as follows:

- Numbers of trials is significantly reduced.
- Important decision variables which control and improve the performance of the product or the process can be identified.
- Optimal setting of the parameters can be found out.
- Qualitative estimation of parameters can be made.
- Experimental error can be estimated.

In the present work, the full factorial method has been used to plan the experiments and subsequent analysis of the data collected.

DESIGN OF EXPERIMENTS

There are large numbers of factors to be considered for MRR calculation in EDM process but in the present work discharge current, pulse on time (Ton), and pulse off time (Toff) have only been taken into account as design factors. The reason why these three factors have been selected as design factors is that they are the most widespread and used amongst EDM researchers.

A *factorial (*Montgomery) experiment is an experimentalstrategy in which design variables are varied together, instead of one at a time.The allowable range is thendiscretized at differentlevels. If each of the variables is defined at only the lower and upperbounds (twolevels), the experimental design is called 2^Nfull factorial.

Similarly, if the midpointsare included, the design is called 3^N full factorial and shown in Figure.

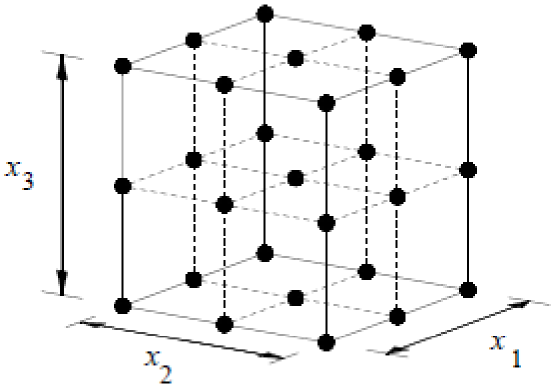

Fig 9 3^3full factorial design (27 points)

Generally, for a largenumber of variables, the number of experiments grows exponentially ($3^N$for a fullfactorial) and becomes impractical. A full factorial design typically is used for fiveor fewer variables.

Response variables

The selected response variables MRR are defined as follows:

Material removal rate was calculated from the difference of weight of work piece before and after machining process

MRR = $(W_i - W_f)/T$ gm/min

Where W_i is the initial weight and $W_f$isthe final weight after machining and T is the total time taken for the machining.

Table 1: Machining Parameters

S.No	Machining Parameters	Fixed Value
1.	Open Circuit Voltage	100V
2.	Polarity	Straight
3.	Depth of cut	1 mm
4.	Type of Di-electric	EDM Oil

Table 2:Machining Condition Used During Experimentation

Electrode	**Workpiece**	**Dielectric fluid**	**Flushing type**
Graphite, φ35mm Thermal conductivity 80 W/m-k Melting point 4800 ^{0}C Electrical resistivity 3.5×10^{-3} ohm-cm Specific heat capacity 7.10 J/g ^{0}C	EN 31 die steel Elements Composition (wt. %) C 1.07 Si 0.32 Mn 0.58 P 0.04 S 0.03 Cr 1.12 V - Fe Balance	EDM Oil Specific Gravity 0.757 Flash Point 108°C Pour Point 0°C, Viscosity cSt @40°C 3.05 Copper Corrosion 1A Di-electric Strength 40	Submerged

Table3:Values of variables at different level

CONTROL FACTORS	1	2	3
Peak current (Amp)	8	10	12
Pulse duration(T_{ON}) (Micro second)	4	6	8
T_{OFF}(Micro second)	3	5	7

Table 4: Experimental results of MRR with 3^N Factors

Exp No	Peak Current	T_{ON}	T_{OFF}	Peak Current	T_{ON}	T_{OFF}	Initial Wt(gm)	Final Wt(gm)	Time taken (min)	MRR (gm/min)
1	1	2	3	8	6	7	565.365	554.253	184	0.0604
2	2	2	3	10	6	7	565.363	558.063	117	0.0624
3	3	2	3	12	6	7	561.131	553.632	78	0.0961
4	1	3	3	8	8	7	599.231	591.921	146	0.05
5	2	3	3	10	8	7	595.912	588.531	97	0.0761
6	3	3	3	12	8	7	530.501	522.481	76	0.1055
7	1	1	3	8	4	7	470.015	464.164	117	0.05
8	2	1	3	10	4	7	465.392	458.911	92	0.0704
9	3	1	3	12	4	7	433.981	426.951	76	0.0925
10	1	2	2	8	6	5	464.162	458.081	51	0.1192
11	2	2	2	10	6	5	458.915	452.531	34	0.1878
12	3	2	2	12	6	5	522.092	516.821	21	0.251
13	1	3	2	8	8	5	570.441	563.43	70	0.1001
14	2	3	2	10	8	5	514.771	507.581	42	0.1712
15	3	3	2	12	8	5	532.352	525.221	38	0.1877
16	1	1	2	8	4	5	533.423	527.812	105	0.0534
17	2	1	2	10	4	5	491.572	486.642	45	0.1096
18	3	1	2	12	4	5	524.014	518.073	54	0.11
19	1	2	1	8	6	3	527.815	520.384	43	0.1728
20	2	2	1	10	6	3	486.642	479.513	30	0.2376
21	3	2	1	12	6	3	442.132	435.121	23	0.3048
22	1	3	1	8	8	3	463.075	456.714	80	0.0795
23	2	3	1	10	8	3	459.915	453.065	58	0.1181
24	3	3	1	12	8	3	435.101	427.391	30	0.257
25	1	1	1	8	4	3	456.712	450.292	104	0.0617
26	2	1	1	10	4	3	453.064	446.945	47	0.1302
27	3	1	1	12	4	3	438.981	433.982	26	0.1922

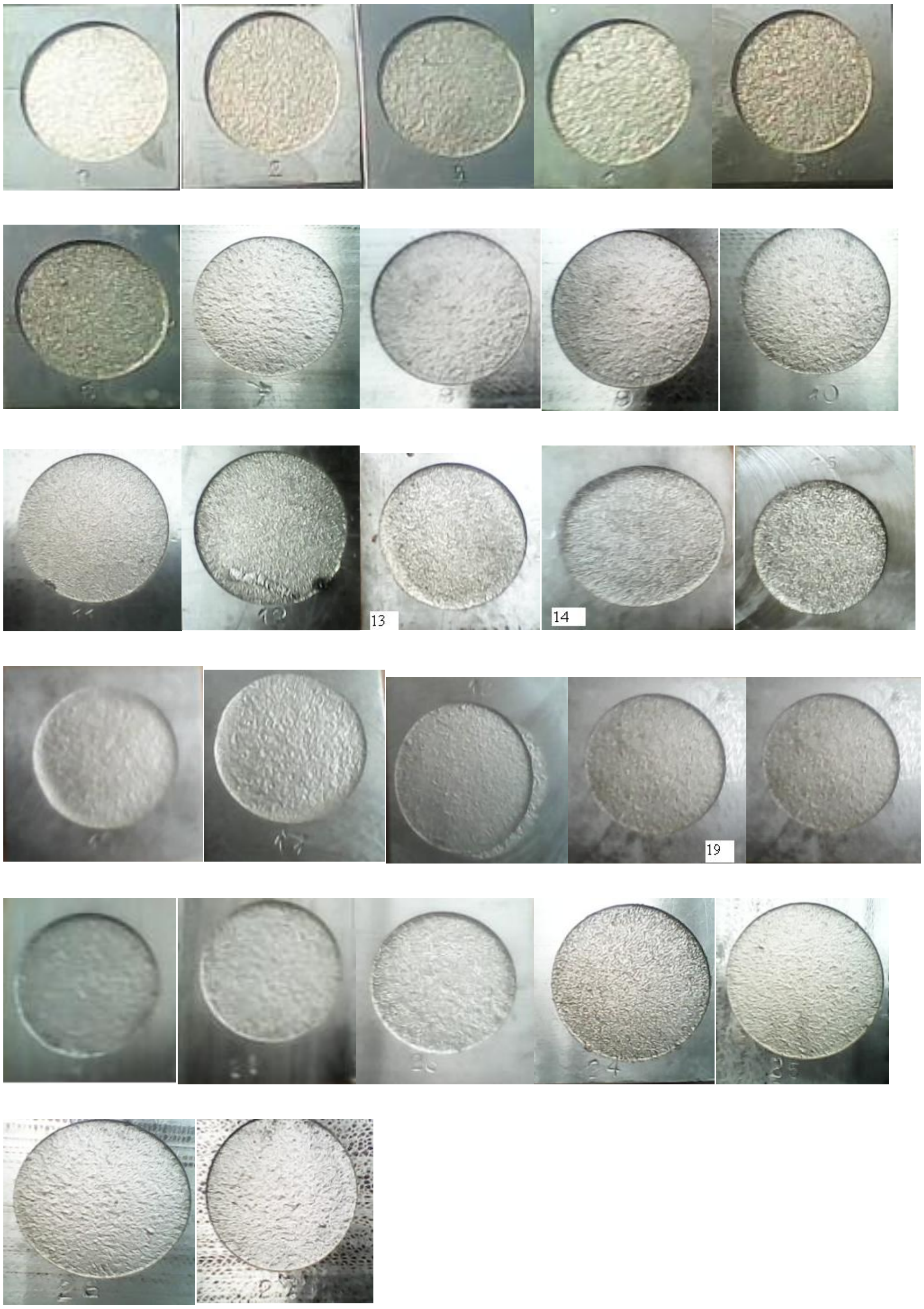

Fig 10 EDM Surface

Table5: Experimental results of MRR with log value

Exp No	Peak Current	T_{ON}	T_{OFF}	Initial Wt(gm)	Final Wt(gm)	Time taken (min)	MRR (gm/min)	log C	log Ton	Log Toff	Log MRR
1	8	6	7	565.365	554.253	184	0.0604	0.90309	0.778151	0.845	-1.21896
2	10	6	7	565.363	558.063	117	0.0624	1.00000	0.778151	0.845	-1.20482
3	12	6	7	561.131	553.632	78	0.0961	1.07918	0.778151	0.845	-1.01728
4	8	8	7	599.231	591.921	146	0.05	0.90309	0.90309	0.845	-1.30103
5	10	8	7	595.912	588.531	97	0.0761	1.00000	0.90309	0.845	-1.11862
6	12	8	7	530.501	522.481	76	0.1055	1.07918	0.90309	0.845	-0.97675
7	8	4	7	470.015	464.164	117	0.05	0.90309	0.60206	0.845	-1.30103
8	10	4	7	465.392	458.911	92	0.0704	1.00000	0.60206	0.845	-1.15243
9	12	4	7	433.981	426.951	76	0.0925	1.07918	0.60206	0.845	-1.03386
10	8	6	5	464.162	458.081	51	0.1192	0.90309	0.778151	0.698	-0.92372
11	10	6	5	458.915	452.531	34	0.1878	1.00000	0.778151	0.698	-0.7263
12	12	6	5	522.092	516.821	21	0.251	1.07918	0.778151	0.698	-0.60033
13	8	8	5	570.441	563.43	70	0.1001	0.90309	0.90309	0.698	-0.99957
14	10	8	5	514.771	507.581	42	0.1712	1.00000	0.90309	0.698	-0.7665
15	12	8	5	532.352	525.221	38	0.1877	1.07918	0.90309	0.698	-0.72654
16	8	4	5	533.423	527.812	105	0.0534	0.90309	0.60206	0.698	-1.27246
17	10	4	5	491.572	486.642	45	0.1096	1.00000	0.60206	0.698	-0.96019
18	12	4	5	524.014	518.073	54	0.11	1.07918	0.60206	0.698	-0.95861
19	8	6	3	527.815	520.384	43	0.1728	0.90309	0.778151	0.477	-0.76246
20	10	6	3	486.642	479.513	30	0.2376	1.00000	0.778151	0.477	-0.62415
21	12	6	3	442.132	435.121	23	0.3048	1.07918	0.778151	0.477	-0.51599
22	8	8	3	463.075	456.714	80	0.0795	0.90309	0.90309	0.477	-1.09963
23	10	8	3	459.915	453.065	58	0.1181	1.00000	0.90309	0.477	-0.92775
24	12	8	3	435.101	427.391	30	0.257	1.07918	0.90309	0.477	-0.59007
25	8	4	3	456.712	450.292	104	0.0617	0.90309	0.60206	0.477	-1.20971
26	10	4	3	453.064	446.945	47	0.1302	1.00000	0.60206	0.477	-0.88539
27	12	4	3	438.981	433.982	26	0.1922	1.07918	0.60206	0.477	-0.71625

Regression Analysis: logMRR versus log C, log Ton, Log Toff

The regression equation is

logMRR = - 2.55 + 1.87 log C + 0.418 log Ton - 0.855 Log Toff ----------(1)

Taking Anti-log of equation (1)

$$MRR=0.0028 \times C^{1.87} \times Ton^{0.418} \times Toff^{-0.855}$$

Predictor	Coef	SE Coef	T	P
Constant	-2.5462	0.4133	-6.16	0.000
log C	1.8674	0.3635	5.14	0.000
log Ton	0.4177	0.2120	1.97	0.061
Log Toff	-0.8548	0.1730	-4.94	0.000

S = 0.135998 R-Sq = 70.4% R-Sq(adj) = 66.5%

Analysis of Variance

Source		SS	MS	F	P
Regression	3	1.01152	0.33717	18.23	0.000
Residual Error	23	0.42540	0.01850		
Total	26	1.43691			

Source	DF	Seq SS
log C	1	0.48821
log Ton	1	0.07183
Log Toff	1	0.45147

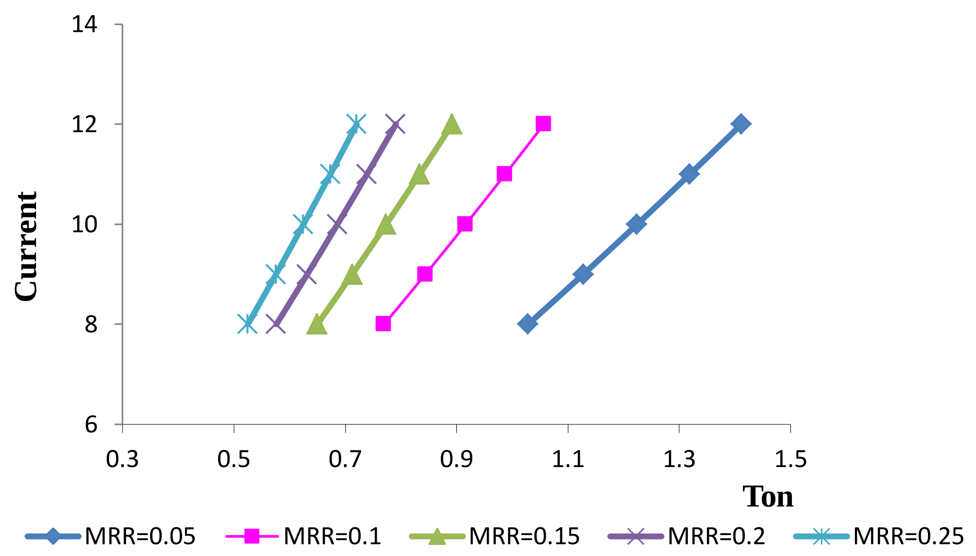

Fig 11 Graph between Current and Ton at Toff=3

As seen from the fig 11, for MRR 0.5, the value of T_{on} varies from 1.02 to 1.41 μs, for MRR 0.1, the value of T_{on} varies from 0.76 to 1.05 μs, for MRR 0.15, the value of T_{on} varies from 0.64 to 0.89 μs, for MRR 0.2, the value of T_{on} varies from 0.57 to 0.79 μs and for MRR 0.25, the value of T_{on} varies from 0.52 to 0.72 μs. It clearly shows that for increasing MRR the value of T_{on} decreasing and when the current increases the value of T_{on} also increases for constant T_{off} at 3μs.

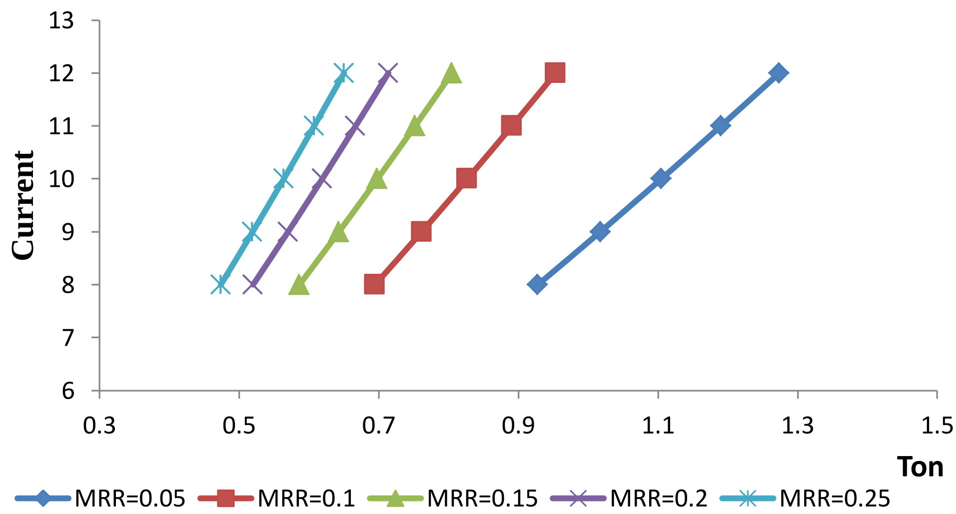

Fig 12 Graph between Current and Ton at Toff=4

As seen from the fig 12, for MRR 0.5, the value of T_{on} varies from 0.92 to 1.27 µs, for MRR 0.1, the value of T_{on} varies from 0.69 to 0.95 µs, for MRR 0.15, the value of T_{on} varies from 0.58 to 0.80 µs, for MRR 0.2, the value of T_{on} varies from 0.51 to 0.71 µs and for MRR 0.25, the value of T_{on} varies from 0.51 to 0.65 µs. It clearly shows that for increasing MRR the value of T_{on} decreasing and when the current increases the value of T_{on} also increases for constant T_{off} at 4µs.

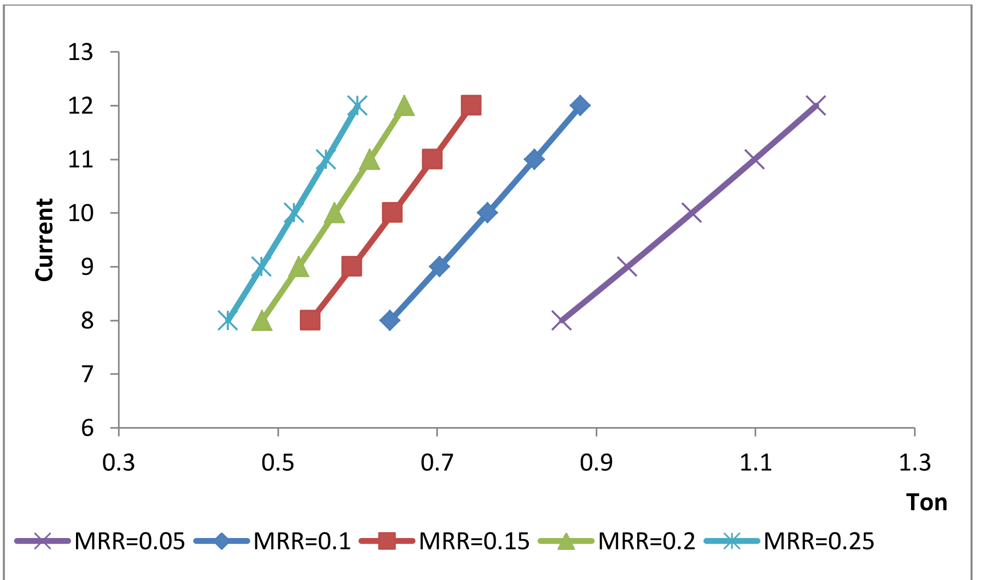

Fig 13 Graph between Current and Ton at Toff=5

As seen from the fig 13, for MRR 0.5, the value of T_{on} varies from 0.85 to 1.17 µs, for MRR 0.1, the value of T_{on} varies from 0.64 to 0.88 µs, for MRR 0.15, the value of T_{on} varies from 0.54 to 0.74 µs, for MRR 0.2, the value of T_{on} varies from 0.47 to 0.65 µs and for MRR 0.25, the value of T_{on} varies from 0.43 to 0.60 µs. It clearly shows that for increasing MRR the value of T_{on} decreasing and when the current increases the value of T_{on} also increases for constant T_{off} at 5µs.

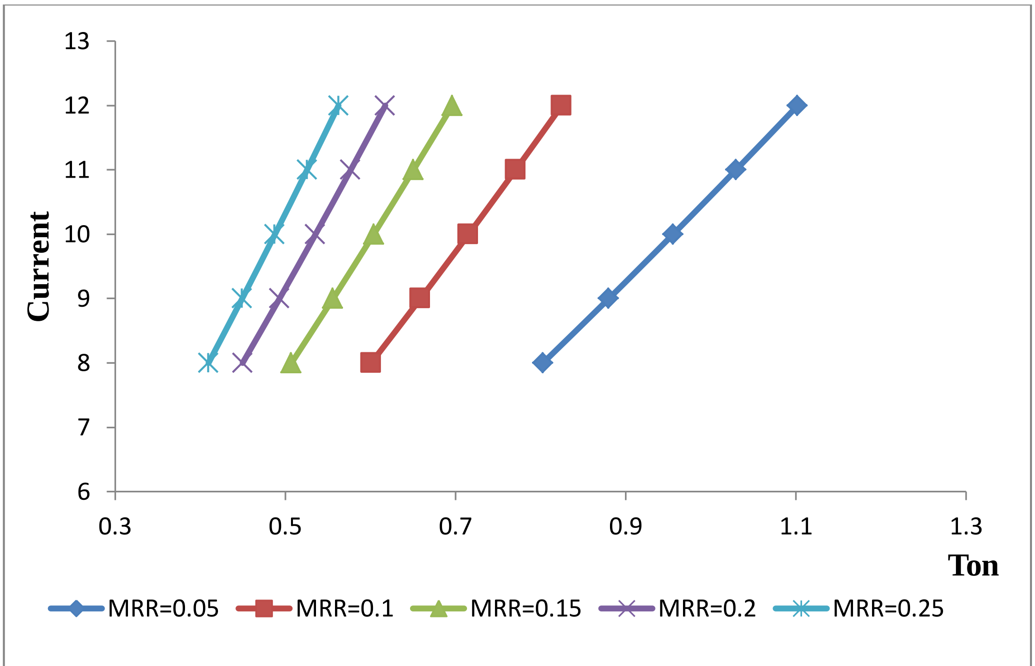

Fig 14 Graph between Current and Ton at Toff=6

As seen from the fig 14, for MRR 0.5, the value of T_{on} varies from 0.08 to 1.10 µs, for MRR 0.1, the value of T_{on} varies from 0.60 to 0.82 µs, for MRR 0.15, the value of T_{on} varies from 0.50 to 0.69 µs, for MRR 0.2, the value of T_{on} varies from 0.44 to 0.61 µs and for MRR 0.25, the value of T_{on} varies from 0.40 to 0.56 µs. It clearly shows that for increasing MRR the value of T_{on} decreasing and when the current increases the value of T_{on} also increases for constant T_{off} at 6µs.

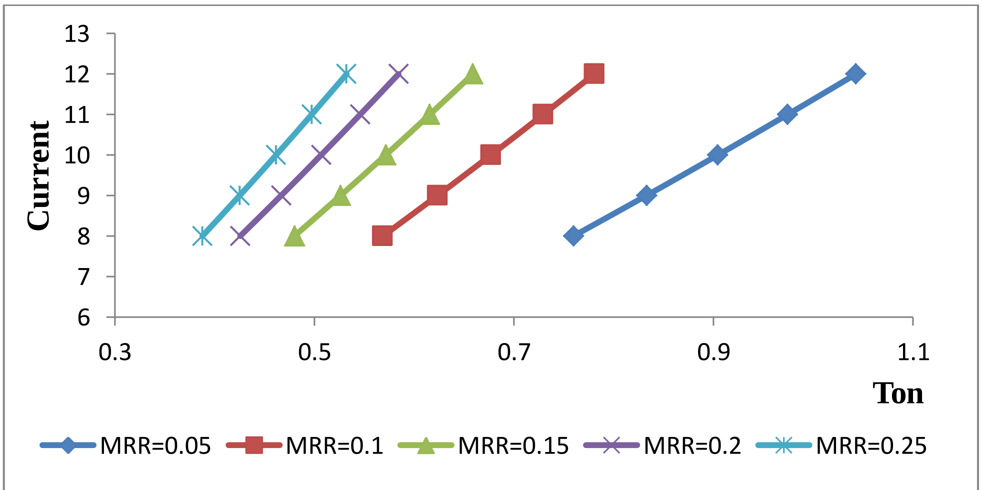

Fig 15 Graph between Current and Ton at Toff=7

As seen from the fig 15, for MRR 0.5, the value of T_{on} varies from 0.75to 1.04 µs, for MRR 0.1, the value of T_{on} varies from 0.56 to 0.78 µs, for MRR 0.15, the value of T_{on} varies from 0.47 to 0.65 µs, for MRR 0.2, the value of T_{on} varies from 0.42 to 0.58 µs and for MRR 0.25, the value of T_{on} varies from 0.38 to 0.53 µs. It clearly shows that for increasing MRR the value of T_{on} decreasing and when the current increases the value of T_{on} also increases for constant T_{off} at 7µs.

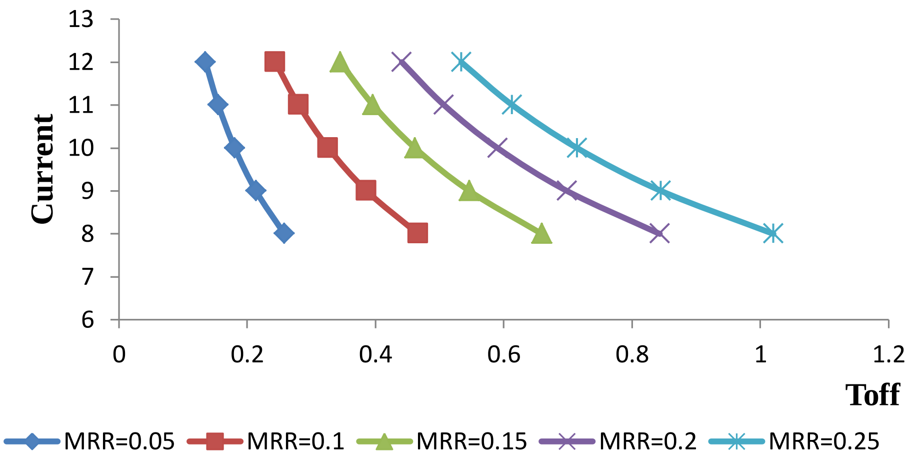

Fig 16 Graph between Current and Toff at Ton=4

As seen from the fig 16, for MRR 0.5, the value of T_{off} varies from 0.25 to 0.13 µs, for MRR 0.1, the value of T_{off} varies from 0.46 to 0.24 µs, for MRR 0.15, the value of T_{off} varies from 0.65 to 0.34 µs, for MRR 0.2, the value of T_{off} varies from 0.84 to 0.44 µs and for MRR 0.25, the value of T_{off} varies from 0.44 to 0.53 µs. It clearly shows that for increasing MRR the value of T_{off}also increasingand when the current increases the value of T_{off} decreases for constant T_{on}at 4µs. But the variation of T_{off} and current with constant T_{on} is not linear.

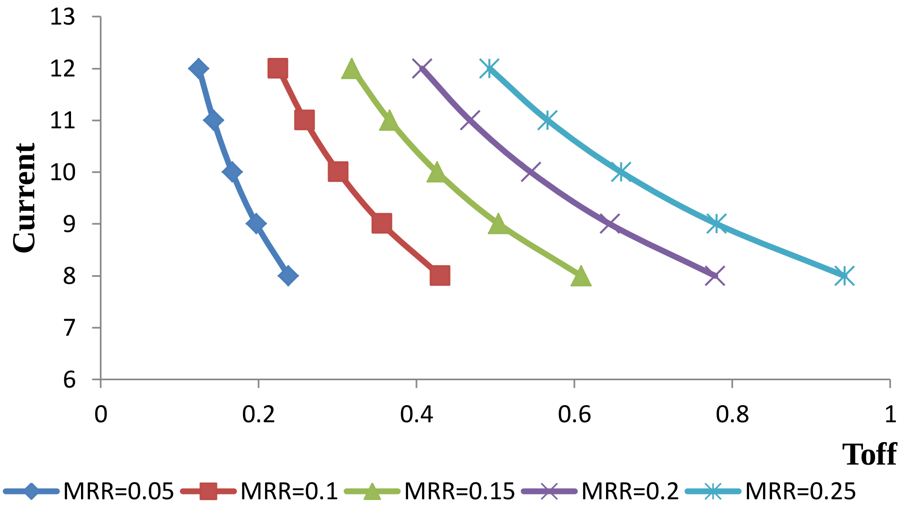

Fig 17 Graph between Current and Toff at Ton=5

As seen from the fig 17, for MRR 0.5, the value of T_{off} varies from 0.23 to 0.12 µs, for MRR 0.1, the value of T_{off} varies from 0.43 to 0.22 µs, for MRR 0.15, the value of T_{off} varies from 0.60 to 0.31 µs, for MRR 0.2, the value of T_{off} varies from 0.77 to 0.40 µs and for MRR 0.25, the value of T_{off} varies from 0.94 to 0.49 µs. It clearly shows that for increasing MRR the value of T_{off} also increasing and when the current increases the value of T_{off} decreases for constant T_{on} at 5µs. But the variation of T_{off} and current with constant T_{on} is not linear.

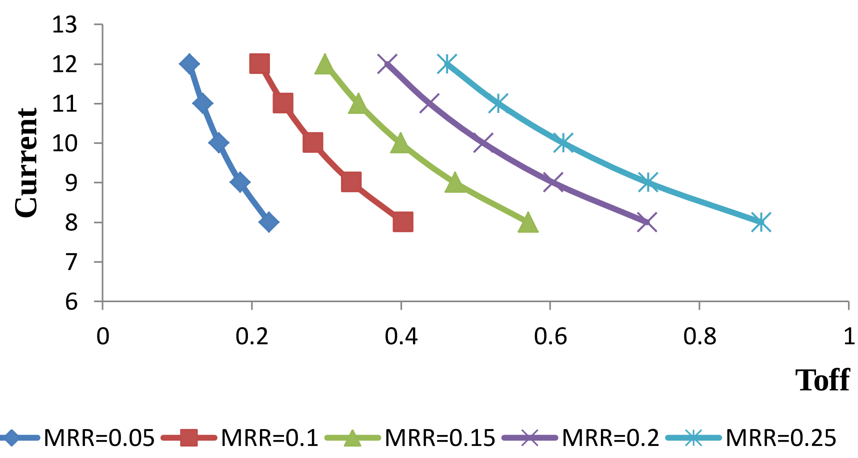

Fig 18 Graph between Current and Toff at Ton=6

As seen from the fig 18, for MRR 0.5, the value of T_{off} varies from 0.22 to 0.11 µs, for MRR 0.1, the value of T_{off} varies from 0.40 to 0.21 µs, for MRR 0.15, the value of T_{off} varies from 0.57 to 0.29 µs, for MRR 0.2, the value of T_{off} varies from 0.72 to 0.38 µs and for MRR 0.25, the value of T_{off} varies from 0.88 to 0.46 µs. It clearly shows that for increasing MRR the value of T_{off} also increasing and when the current increases the value of T_{off} decreases for constant T_{on} at 6µs. But the variation of T_{off} and current with constant T_{on} is not linear.

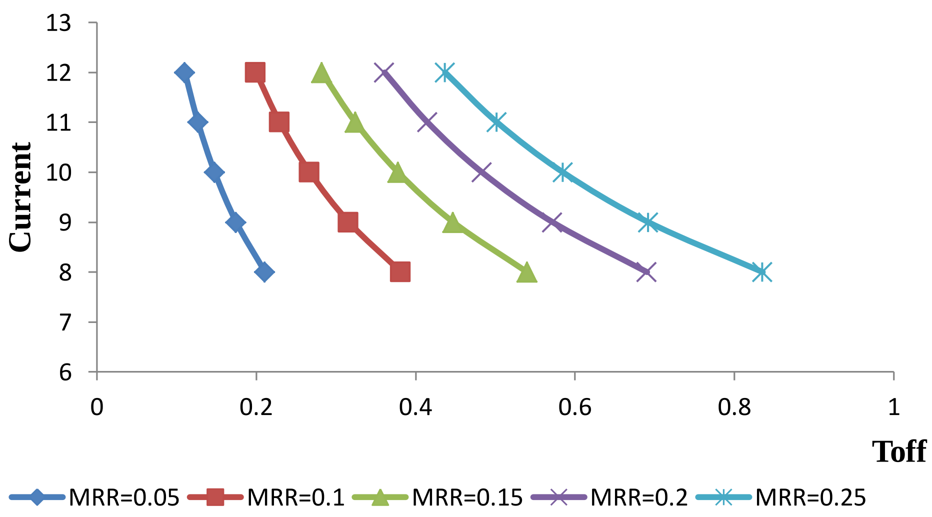

Fig 19 Graph between Current and Toff at Ton=7

As seen from the fig 19, for MRR 0.5, the value of T_{off} varies from 0.21 to 0.11 µs, for MRR 0.1, the value of T_{off} varies from 0.38 to 0.19 µs, for MRR 0.15, the value of T_{off} varies from 0.53 to 0.28 µs, for MRR 0.2, the value of T_{off} varies from 0.69 to 0.36 µs and for MRR 0.25, the value of T_{off} varies from 0.83 to 0.43 µs. It clearly shows that for increasing MRR the value of T_{off} also increasing when the current decreases with increase in T_{off} for constant T_{on} at 7µs. But the variation of T_{off} and current with constant T_{on} is not linear.

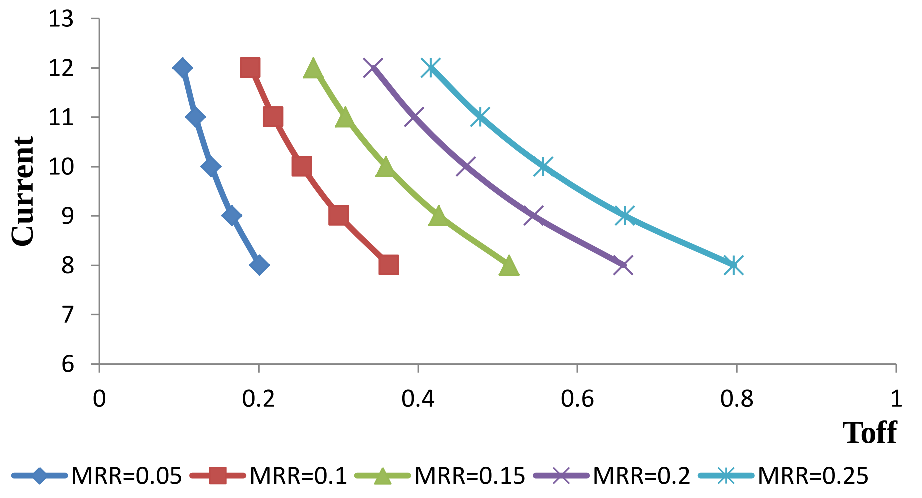

Fig 20 Graph between Current and Toff at Ton=8

As seen from the fig 20, for MRR 0.5, the value of T_{off} varies from 0.20 to 0.10 µs, for MRR 0.1, the value of T_{off} varies from 0.36 to 0.19 µs, for MRR 0.15, the value of T_{off} varies from 0.51 to 0.26 µs, for MRR 0.2, the value of T_{off} varies from 0.65 to 0.34 µsand for MRR 0.25, the value of T_{off} varies from 0.79 to 0.41 µs. It clearly shows that for increasing MRR the value of T_{off} also increasing and when the current increases the value of T_{off} decreases for constant T_{on} at 8µs. But the variation of T_{off} and current with constant T_{on} is not linear.

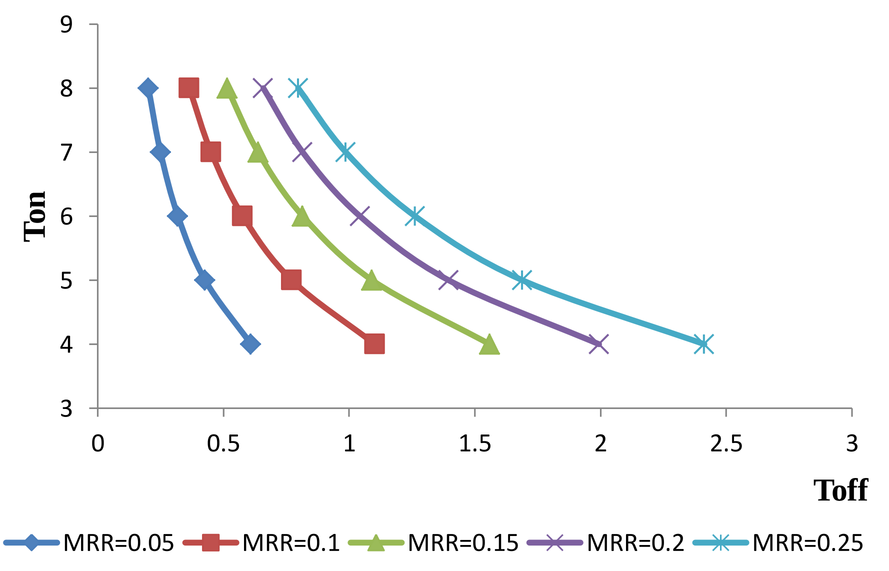

Fig 21 Graph between Ton and Toff at Current=8

As seen from the fig 21, for MRR 0.5, the value of T_{off} varies from 0.60 to 0.20 µs, for MRR 0.1, the value of T_{off} varies from 1.10 to 0.36 µs, for MRR 0.15, the value of T_{off} varies from 1.55 to 0.51 µs, for MRR 0.2, the value of T_{off} varies from 1.99 to 0.65 µs and for MRR 0.25, the value of T_{off} varies from 2.41 to 0.79 µs. It clearly shows that for increasing MRR the value of T_{off} also increasing and while the T_{on}increases the value of T_{off} decreases for constant Currentat 8 amps. But the variation of T_{off} and $T_{on}$with constant current is not linear.

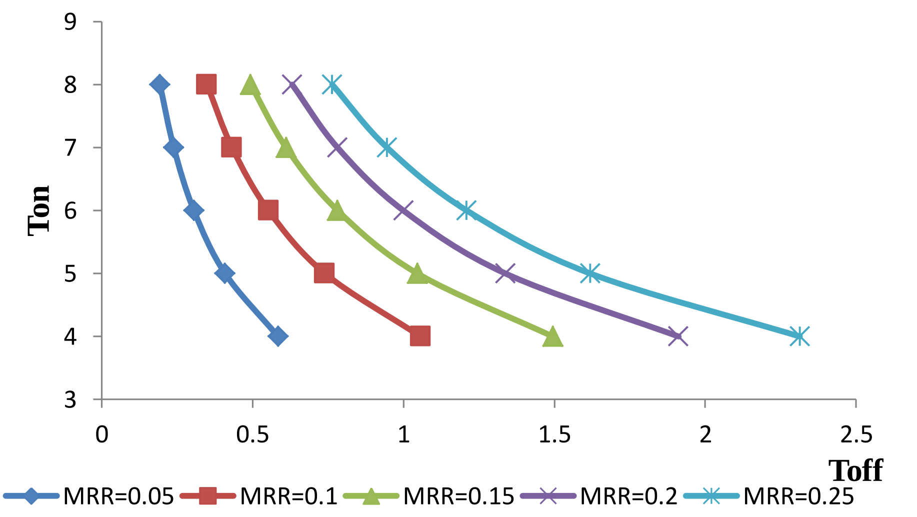

Fig 22 Graph between Ton and Toff at Current=9

As seen from the fig 22, for MRR 0.5, the value of T_{off} varies from 0.58 to 0.19 µs, for MRR 0.1, the value of T_{off} varies from 1.05 to 0.34 µs, for MRR 0.15, the value of T_{off} varies from 1.49 to 0.49 µs, for MRR 0.2, the value of T_{off} varies from 1.91 to 0.63 µs and for MRR 0.25, the value of T_{off} varies from 2.31 to 0.76 µs. It clearly shows that for increasing MRR the value of T_{off} also increasing and while the T_{on} increases the value of T_{off} decreases for constant Currentat 9 amps. But the variation of T_{off} and T_{on} with constant current is not linear.

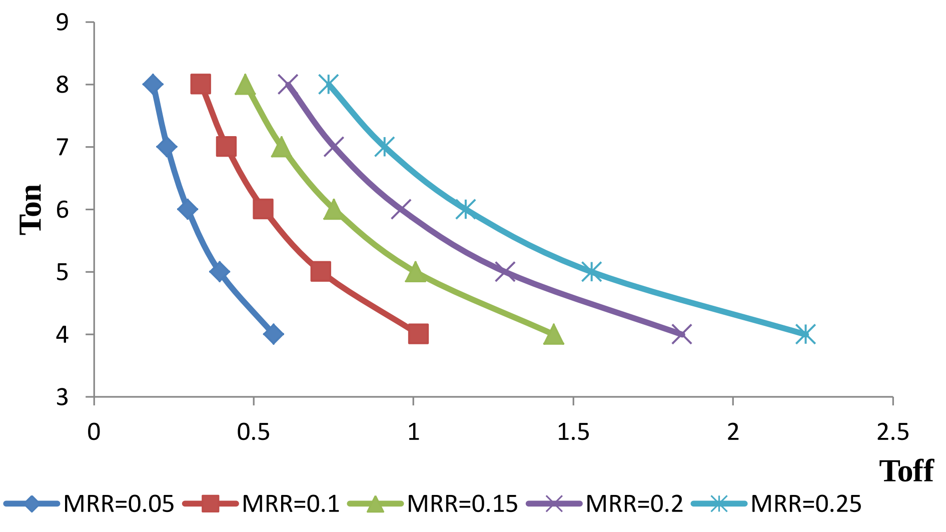

Fig 23 Graph between Ton and Toff at Current=10

As seen from the fig 23, for MRR 0.5, the value of T_{off} varies from 0.56 to 0.18 µs, for MRR 0.1, the value of T_{off} varies from 1.01 to 0.33 µs, for MRR 0.15, the value of T_{off} varies from 1.43 to 0.47 µs, for MRR 0.2, the value of T_{off} varies from 1.84 to 0.60 µs and for MRR 0.25, the value of T_{off} varies from 2.22 to 0.73 µs. It clearly shows that for increasing MRR the value of T_{off} also increasing and while the T_{on} increases the value of T_{off} decreases for constant Currentat 10 amps. But the variation of T_{off} and T_{on} with constant current is not linear.

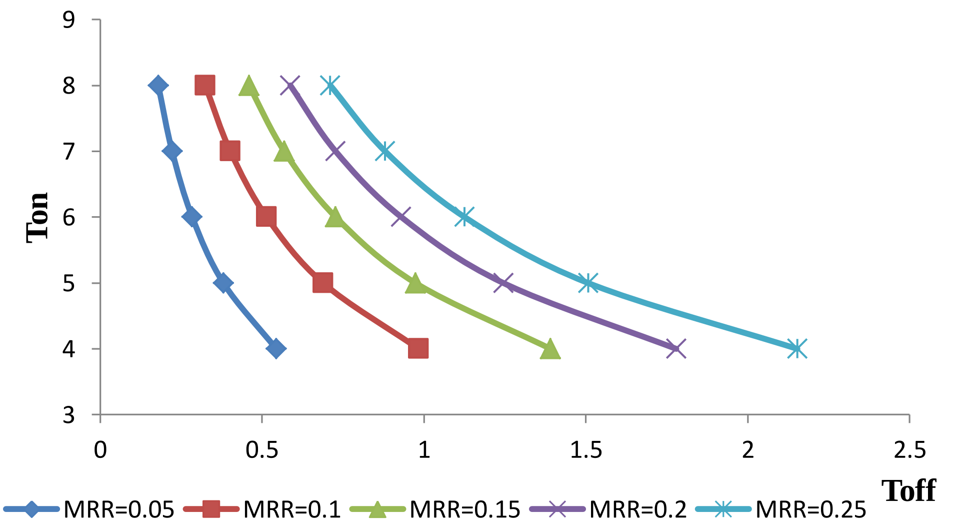

Fig 24 Graph between Ton and Toff at Current=11

As seen from the fig 24, for MRR 0.5, the value of T_{off} varies from 0.54 to 0.17 µs, for MRR 0.1, the value of T_{off} varies from 0.98 to 0.32 µs, for MRR 0.15, the value of T_{off} varies from 1.39 to 0.45 µs, for MRR 0.2, the value of T_{off} varies from 1.77 to 0.58 µs and for MRR 0.25, the value of T_{off} varies from 2.15 to 0.71 µs. It clearly shows that for increasing MRR the value of T_{off} also increasing and while the T_{on} increases the value of T_{off} decreases for constant Currentat 11 amps. But the variation of T_{off} and T_{on} with constant current is not linear.

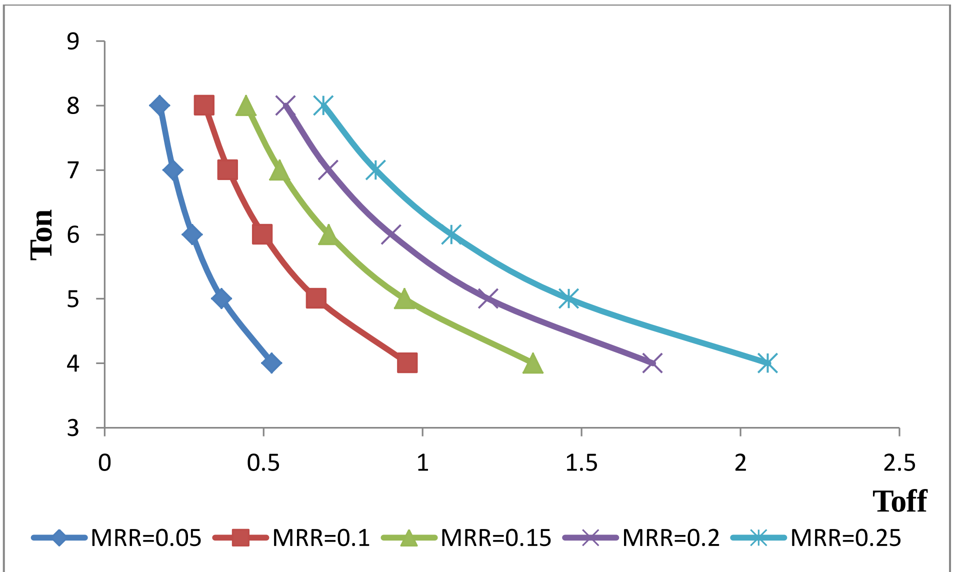

Fig 25 Graph between Ton and Toff at Current=12

As seen from the fig 25, for MRR 0.5, the value of T_{off} varies from 0.52 to 0.17 µs, for MRR 0.1, the value of T_{off} varies from 0.95 to 0.31 µs, for MRR 0.15, the value of T_{off} varies from 1.34 to 0.44 µs, for MRR 0.2, the value of T_{off} varies from 1.20 to 0.56 µs and for MRR 0.25, the value of T_{off} varies from 2.08 to 0.68 µs. It clearly shows that for increasing MRR the value of T_{off} also increasing and while the T_{on} increases the value of T_{off} decreases for constant Currentat 8 amps. But the variation of T_{off} and T_{on} with constant current is not linear.

CHAPTER 6

CONCLUSIONS AND FUTURE SCOPE OF WORK

Conclusion:

The manufacturing parameters are one of the most important aspects in the electrical discharge machining operation as these conditions has important effect on material removal rate (MRR). The experiments have been conducted on the EN 31 die steel with graphite electrode with electrical discharge machining (EDM). The EDM oil commercial grade has been used as dielectric fluid. The effect of various EDM parameters such as discharge current, T_{on} and T_{off} has been investigated to yield the response in terms of MRR. In this work mathematical models have been developed for relating the MRR with machining parameters like discharge current, T_{on}, and T_{off}. With the help of MINITAB 15 software mathematical modeling has been done. After analyzing the results the following conclusions are arrived at:

(i) MRR increases with increase in discharge current. The enhancement in MRR may be attributed due to increase in pulse energy as the current increases.

(ii) At higher levels of current, wear rate of graphite increases and causes some machining problems which further reduces MRR. This may be due to arcing produced at high current densities.

(iii) With increase in Ton for same discharge current the MRR decreases.

(iv) With increase in Toff for the same current the MRR decreases.

(v) With lower Toff the MRR is more as compared to lower Ton.

(vi) It is analysed that for a particular value of *Toff*, for increasing MRR the value of T_{on} decreasing and when the current increases the value of T_{on} also increases.

(vii) It is analysed that for a particular value of *Ton*, for increasing MRR the value of T_{off} also increasing and when the current increases the value of T_{off} decreases. But the variation of T_{off} and Current is not linear for constant $T_{on.}$

(viii) It is analysed that for a particular value of *Current*, for increasing MRR the value of T_{off} also increasing and while the T_{on} increases the value of T_{off} decreases. But the variation of T_{off} and T_{on} with constant current is not linear.

Future Scope of Work

- Different Tool materials can be used.
- Side clearance and thermal effect on material and work piece can also be considered to study the effect on properties of work piece and tool.
- Other modeling method like genetic algorithm, artificial neural network and fuzzy logic can also be applied.
- Other parameters like flushing etc. can also be considered.

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